

AD-A130 376

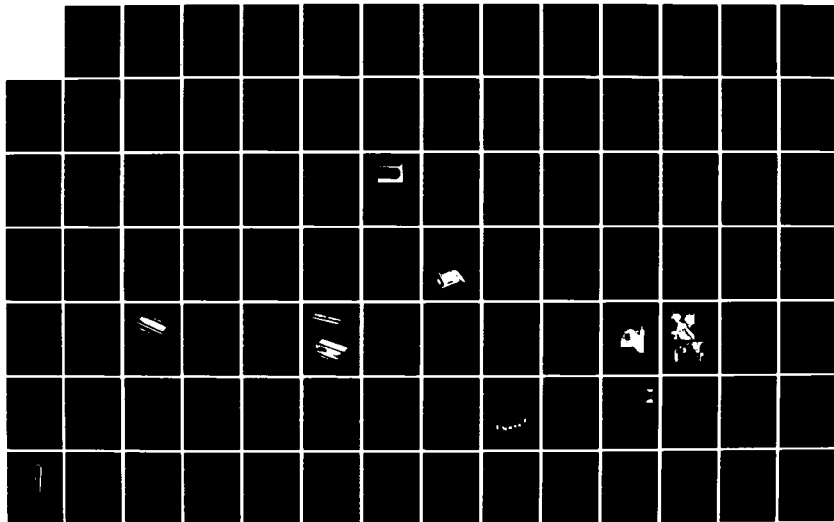
DEVELOPMENT OF A GENERATOR STATOR INSULATION SYSTEM(U)
HUGHES AIRCRAFT CO CULVER CITY CA TECHNOLOGY SUPPORT
DIV R 5 BURITZ APR 83 FR-83-76-686 DAAK78-79-C-0131

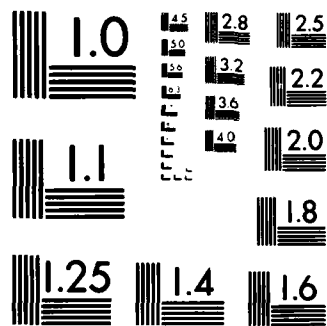
1/2

UNCLASSIFIED

F/G 10/2

NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

ADA130376

(12)

REPORT NO. ER83 76 686
HAC REF. NO. E5112

FINAL REPORT

DEVELOPMENT OF A GENERATOR STATOR INSULATION SYSTEM

APRIL 1983

HUGHES
HUGHES AIRCRAFT COMPANY
**ELECTRO-OPTICAL AND
DATA SYSTEMS GROUP**

DTIC
ELECTE
S JUL 12 1983
A

DTIC FILE COPY

83 07 12 036

This document has been approved
for public release and its
distribution is unlimited.

Report No. FR83-76-686
HAC Ref. No. E5112

DEVELOPMENT OF A GENERATOR STATOR
INSULATION SYSTEM

April 1983

Electro-Optical and Data Systems Group
Hughes Aircraft Company • El Segundo, California 90245



Accession For	
DTIC GRA&I	<input checked="" type="checkbox"/>
TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Distribution/	
Available to the Public	
Author	
1	

Little

A

FOREWORD

This is the final report of the development of an insulation system for a generator stator supported by the U.S. Army Mobility Equipment Research and Development Command at Fort Belvoir, Virginia, under Contract DAAK 70-79-C-0131. The program was monitored by Mr. Carl J. Heise of the Electrical Machinery Branch. The program manager and principal investigator at Hughes Aircraft Company was Mr. Robert S. Buritz.

The work described herein was conducted by the Technology Support Division of the Hughes Aircraft Company at its Culver City, CA facility, except the skewed mold which was machined by the Missile Development Division, Canoga Park, CA. The straight molds were machined by the Tactical Engineering Division.

Mr. Victor I. Mizuno was responsible for the impregnation and process engineering and assisted in the design of the molds. Mr. Henry A. Szewczyk developed the processing and impregnated the coils. Mr. Watson H. Kilbourne designed the molds. Mr. Clyne K. Sasaki was responsible for making the straight molds and assisted in the design of the molds. Mr. John C. Scannell was responsible for making the skewed mold. Mr. Roy E. May planned the machining of the skewed mold, designed critical tooling, and wrote the computer program for the machining.

Mr. Robert D. Gourlay designed the life test system and performed the thermal analysis. Dr. Robert D. Parker did the wire evaluation and wrote the Test Plan. Mr. Donald R. McWilliams constructed the life test system. Mr. Richard Salisbury conducted the investigation of candidate materials. Dr. Donald C. Smith and Mr. Richard Holbrook consulted on oil compatibility. Mr. Richard A. Livingston designed and carried out the

thermal conductivity measurements. Mrs. Linda K. Lemmon conducted the corona measurements. Mr. Edward G. Wong was responsible for the conductive solution study.

Messrs. Alfred W. Wohlberg and Vince J. Soviero, Jr. of Bendix Electric Power Division, Eatontown, New Jersey, supplied the coils and assisted in evaluating the coils in the stator.

SUMMARY

An important aspect of the program was to select the dielectric to be used. The most promising dielectrics were screened using test models. The material selected was an epoxy/glass system using Epon 825 with HV hardener. Extensive testing demonstrated the suitability of the material. The breakdown voltage was about 6 kV between turns and greater than 15 kV to ground. Tensile specimens of epoxy/glass immersed in oil for 250 hours at temperatures up to 230°C indicated that the insulation should operate safely at temperatures up to 190°C.

A simple steel mold was used to encapsulate the first coils. After encapsulation the dimensions varied only a few mils, the thickness of the epoxy was uniform around the coil, and it was free of voids. The only problem was flash at the corners which was difficult to remove without damaging the insulation. The mold was redesigned to have the parting line at the side so it could be closed tightly, eliminating any flash. Coils made using this mold were used for the second and third life tests which operated successfully for 1500 and 2200 hours respectively.

The thermal conductivity of samples of ML wire insulated with epoxy was measured as part of the selection criteria. For ML wire alone, the thermal conductivity $k = 0.11 \text{ BTU hr}^{-1} \text{ ft}^{-1} \text{ }^{\circ}\text{F}^{-1}$, for ML wire and polyweb insulation $k = 0.13$, for ML wire with glass insulation $k = 0.19$.

Epoxy/glass samples and a coil were temperature cycled from 0 to 200°C for 30 cycles in air. There was no change in the CIV or evidence of any degradation of the insulation.

Measuring the turn-to-turn breakdown voltage for a coil required a special transformer whose secondary was a stator coil to induce 200 volts per turn in a coil. The coils were tested at 4.5 times the rated voltage with no failures.

To detect cracks and pinholes, a screening test was developed that uses a conductive solution. Small holes only a few mils in diameter can be readily located. The test is non-destructive.

The adequacy of the insulation was determined by life testing under simulated full power conditions, with 100°C ambient cooling oil. The initial test was run with six coils. One failed during the first few hours. The remaining five coils operated without incident for 485 hours. The second and third life tests were conducted with coils made using an improved mold. The parting line on this mold was located on the side, eliminating flash and attendant cracks and nicks. In addition, dimples were added to the mold which provided protuberances on the coil for centering it in the slot. The second life test had three coils that had run for 1100 hours and two coils that had run for 1400 hours when the testing was stopped. One coil failed at 900 hours. The third life test had five coils that had run 2200 hours when the test was terminated. One coil failed at 800 hours.

The life test coils showed a general degradation where the epoxy appeared to have been eroded, baring the glass cloth. The degradation appeared to be temperature and time related; the erosion being greatest at the hottest portions of the coil. Where the coil was cool, there was no apparent damage. It is felt that the degradation is probably a combination of thermal, chemical, and electrical effects which progress rather slowly.

The above molds were designed for straight coils to simplify the tooling. The next step was designing tooling to fabricate coils skewed to fit the stator. Ten coils were fabricated and were assembled in a stator. The coils were an exact fit and installed easily.

A successful insulation system has been developed and amply demonstrated. The insulation system has excellent oil compatibility and superior thermal conductance. The coils operate satisfactorily at full power and at actual service temperatures. The coil life time appears to be more than 1000 hours.

CONTENTS

I	INTRODUCTION	1
	Background	1
	Technical Approach	3
	Development	3
	Prototype Engineering	4
II	PERCEPTION OF PROBLEM	7
	Coil Fabrication	7
	Assembly Into Stator	8
	Thermal Stress	10
	Coil Temperature Rise	10
	Thermal Conductivity Measurement	11
	Oil Compatibility	12
	Fields in the Slot	12
	Corona in Insulation Defects	14
	Electrical Quality of Cooling Oil	15
	Temperature	16
	Life Test Evaluation	16
	Coil Wire	18
	ML Coating	18
	Wire Irregularities	19
	Hughes Approach	21
III	MATERIAL SELECTION	23
	Field Control	23
	Coil Construction	25
	Thermal	26
	Insulation Material Requirements	26
	Selection Factors	26
	Candidate Dielectrics	28
	Evaluation of Candidate Dielectrics	30
	Examination of Means of Processing	30
	Construction of Test Samples	33

CONTENTS (Continued)

Electrical Tests	34
Oil Compatibility	38
Insulation System Selected	41
IV COIL FABRICATION EFFORT	45
Insulation System Construction	45
Mold Design	45
Processing	56
Repair	57
Summary of Coil Development	57
V PROOF OF DESIGN TESTS	59
Thermal Conductivity	60
Experimental Procedure	60
Results	62
Temperature Cycling	64
Dielectric Breakdown	64
Design of Turn-to-Turn Test Apparatus	64
Results	67
Bending Tests	68
Conductive Solution Test	71
Life Tests	71
Description of Generator	71
Life Test Apparatus	73
Startup of Life Test	73
First Life Test	76
Second Life Test	78
Oil Evaluation	81
Third Life Test	82
Results	84
VI RESULTS AND CONCLUSIONS	85
APPENDIX A PURCHASE DESCRIPTION FOR DEVELOPMENT OF A GENERATOR STATOR INSULATION SYSTEM . . .	A-1
APPENDIX B SUMMARY OF CONTRACT MODIFICATIONS	B-1
APPENDIX C TEST PLAN	C-1

CONTENTS (Continued)

APPENDIX D	SLOT SIMULATOR TEST FIXTURE.	D-1
APPENDIX E	COIL MOLD.	E-1
APPENDIX F	BOX MOLD.	F-1
APPENDIX G	REDESIGNED COIL MOLD.	G-1
APPENDIX H	REDESIGNED BOX MOLD	H-1
APPENDIX I	DESIGN CALCULATIONS FOR TURN TO TURN TEST APPARATUS	I-1
APPENDIX J	TURN TO TURN TEST FIXTURE	J-1
APPENDIX K	CONDUCTIVE SOLUTION.	K-1

ILLUSTRATIONS

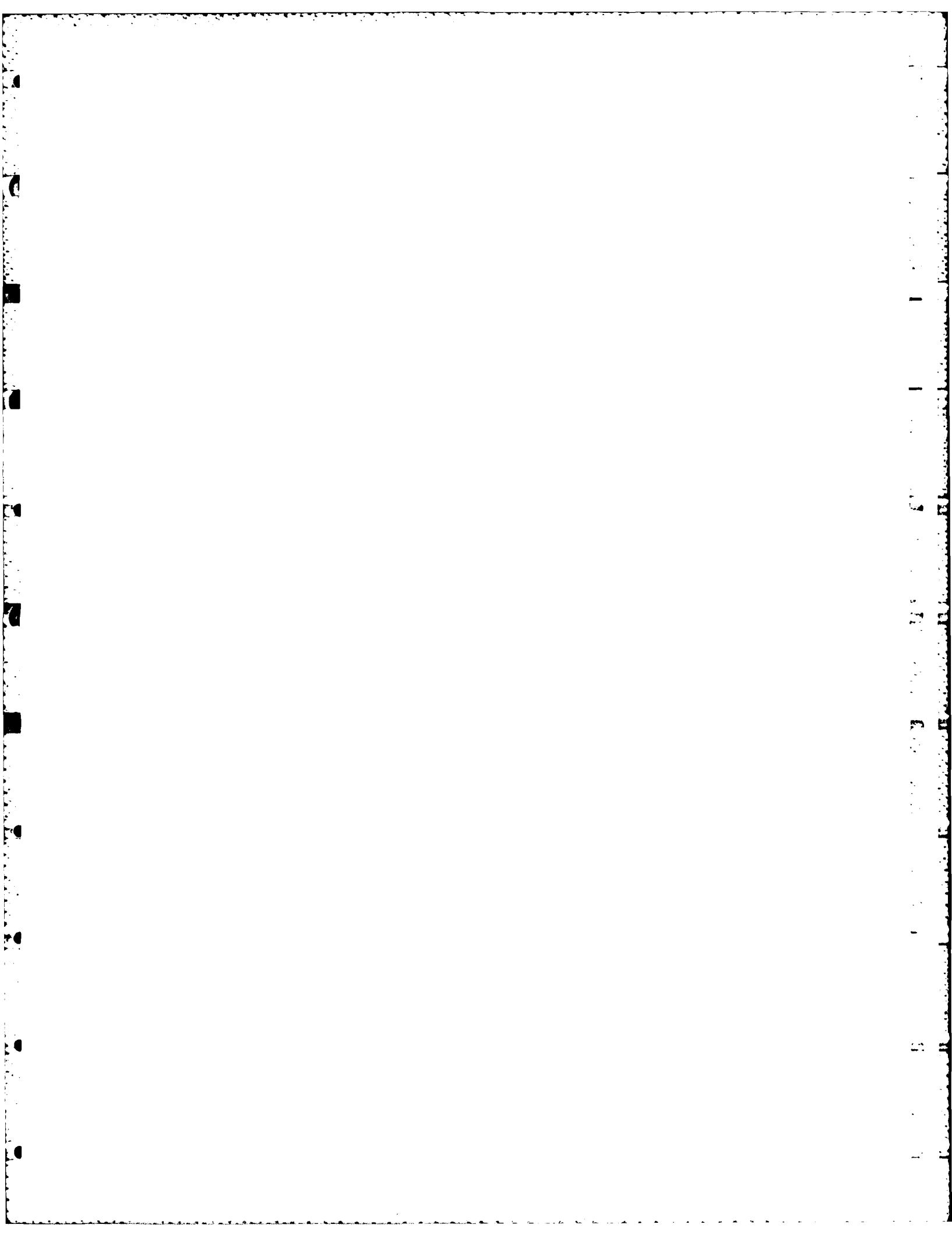
Figure		Page
1	Section View Showing Coil is Wider than Slots	8
2	Configuration of Stator Showing Coil Arrangement at Beginning of Coil Installation	9
3	Typical Slot Showing Coil and Insulation	14
4	Corona Inception Stress Over Insulation Versus Void Size for Different Dielectric Constants	15
5	Thermal Life Unvarnished Pyre - ML Coated Wire	19
6	Section of Wire with Rounded Edges	20
7	Metallographic Cross Section of ML Magnet Wire	21
8	Tape Wrapped Coil Edge Structure	22
9	Placement of Ground Plane to Contain Field in Insulating Wrap	24
10	Termination of Coil Lead Showing Field Control Shield, Cross Section	25
11	Slot Simulator Test Fixture With Slot Covers and Test Samples	36
12	Effect of Oil at Elevated Temperatures for 250 Hours on Epoxy Glass Laminates	42
13	Coil Mold and Glass Tape Wrapped Coil	46
14	Cross Section of Coil Mold	46
15	Mold for Straight Segments	48
16	Redesigned Coil Mold and Coil	49
17	Redesigned Box Mold.	49
18	Skewed Mold	51
19	Bosto-Matic Numerically Controlled Four Axis Precision Drilling Machine.	54

ILLUSTRATIONS (Continued)

Figure		Page
20	Closeup of Upper Mold Half	55
21	Fixture for Lower Mold Half	55
22	Apparatus for Measuring Thermal Conductivity	61
23	Thermal Conductivity Test Specimen	61
24	Resistance of Copper Wire Versus Temperature at Constant Current	62
25	Turn-to-Turn Test Fixture	66
26	Waveforms ($V = 1 \text{ kV/cm}$, 1600 Hz)	68
27	Bending of Pitch Coil During Installation	69
28	Full Coil Life Test Fixture	70
29	Coil Test in Conductive Solution, Coil S/N 9	72
30	Life Test Schematic	74

TABLES

Table		Page
1	Field Versus Varnish Thickness	13
2	Properties of Magnet Wire Coated with Pyre-ML	20
3	Insulation Material Requirements	27
4	Selection Factors and Requirements	28
5	Comparison of Candidate Materials Versus Selection Factors	29
6	Properties of Epon 825/HV and G. E. 707	32
7	Construction of Straight Wire Test Samples	34
8	CIV Between Layers for Six-Layer Straight Segments	35
9	Thermal Conductivity of Stator Coil Insulation Systems	36
10	CIV for Six-Layer Straight Segments Using Slot Simulator	37
11	Breakdown Voltage for Epoxy Dielectric	37
12	Effect of Oil at 200°C on Epoxy/Glass Dielectric	39
13	Change in Volume-Resistivity for Epoxy/Glass Dielectric after Prolonged Exposure to Oil at 170 and 200°C	40
14	Effect of Temperature Cycling 0 to 200°C on Epoxy/Glass Dielectric	65
15	Summary of Breakdown Tests	69
16	System Checkout and Startup	75
17	Coil Temperature for 100°C Ambient Oil	76
18	Failure Analysis of Life Test Coils	78
19	Comparison of Mil-L-7808 Oil Samples	81
20	Change in Oil Condition with Time at 100°C Ambient, Sample 3	82



I. INTRODUCTION

BACKGROUND

The insulation of stator windings in generators is an old technology, dating to the turn of the century with kraft paper insulated, oil filled cables. Over the years insulation systems and assembly methods have improved gradually--notably with the introduction of superior impregnating resins, but for the most part the art of winding a stator remains unchanged. The windings are made from varnish-insulated wire and are either enclosed in a fold of sheet insulation or wrapped with tape insulation. These windings are then stuffed into the jagged, uneven stator slots, and secured in place with wedges pounded in with a hammer. Only in large, extremely expensive power generators and continuous duty motors are the windings encapsulated in the stator slots; here resin is poured in on top of the windings after they are pounded in place.

Various insulation systems have been used for stator insulation. A few of the more common include:

1. Insulating paper (fish paper)
2. Mica tape
3. Mica tape and epoxy
4. Nomex
5. Sheet polyester
6. Fiberglass cloth and resin
7. Fiberglass, plastic sheet, epoxy
8. Polyimide tape
9. Polyimide and teflon

All systems employ magnet wire or bar, commonly insulated with polyvinyl formal, polyester, polyamide, or polyimide coatings. Any system can be impregnated in place after installation, most commonly with polyester resin.

If these techniques seem somewhat primitive when compared with modern aerospace insulation systems, there is good reason. The pieces of apparatus that require long-lived stator windings are large, heavy, and permanently installed. They tend to have extremely small power densities, and there is virtually no pressure to make the machinery smaller and lighter. Essentially classic insulations are designed into the equipment and, like the kraft-oil power cables, performance is acceptable so long as known physical and environmental limits are not exceeded.

Recently, two new classes of machines requiring much more advanced techniques of insulation have emerged. These generators are designed for relatively short duty in situations where light weight and small size are crucial to the overall mission, and mobility is a must. One class of machines uses superconducting windings to achieve small size. The other class consists of conventional generators designed to have extremely high power densities and specific powers. These machines represent a considerable engineering achievement, being significantly smaller than any previous generator. In one of these generators,* manufactured by Bendix, substantial problems have been encountered in the stator winding insulation, because of the high fields dictated by the extremely high power density. This report presents the Hughes Aircraft Company approach and solution to these problems.

*A. L. Jokl and C. J. Heise, "Advanced Generator Technology," Proceedings of the 1976 Pulsed Power Systems Workshop, DDRE, 1977.

TECHNICAL APPROACH

The three logical steps in the development of this coil insulation system are outlined below:

1. Selection of encapsulating materials, preliminary development of application techniques, engineering of preliminary configurations, and preliminary testing
2. Design of tooling and final manufacturing processes, design of coils taking into account actual peculiarities of the generator, development of a program to screen coils to be used in an actual machine
3. Fabrication of coils in final form, test in an actual generator under service conditions.

Normally one would think of the first item as Development, the second as Manufacturing or Prototype Engineering, and the last as Production.

This program was divided into six tasks, comprising Development and Prototype Engineering. These tasks are described in detail in the sections that follow. Each is summarized below.

Development

Selection of an Insulation System. An optimum insulation system to meet the requirements of the Purchase Description will be selected. This selection will consider the voltage capabilities, thermal conductivity, temperature rating, toughness, flexibility, oil compatibility, fabrication requirements and installation conditions. The selection will include testing of candidate materials, some of which will be in short coil sections to evaluate properties that require application to the copper before test.

Development of a Fabrication Method. A fabrication method appropriate for the chosen insulation system will be developed. The elimination of voids and flaws, control of dimensions, and reproducibility will be emphasized. This task will include the definition of specific fabrication processes such as preparation and cleaning, drying methods, curing techniques, and where applicable, mold design and evaluation. A variety of tests will be performed to evaluate the candidate methods and to assure a minimum of process corrections during proof-of-design tests.

Fabrication of Coils. A quantity of fully insulated coils will be fabricated from the selected materials and processes for the proof-of-design tests. The number of coils to be fabricated will be determined in the development of the test plan. The uninsulated coils for this work will be Government furnished.

Proof-of-Design Tests. The proof-of-design tests will be performed in conformance with the requirements of Attachment 1 of the solicitation. Test fixtures will be designed and fabricated to properly simulate the stator slot usage of the coils. An oil circulation system will provide the required oil flow and temperature. This test fixture will be suitable for all the required electrical tests and the life tests. A thermal test fixture will be fabricated and used to measure the heat conductivity of the insulation system so that essentially the temperature drop across the insulation to fluid interface will be eliminated. A test method that is very sensitive to cracks will be used to evaluate the resistance to bending and twisting stress. The proof-of-design test results will be evaluated to provide valid confidence that the developed insulation system meets program requirements.

Prototype Engineering

Manufacturing/Prototype Engineering. Suitable gauges will be designed to check coil dimensions. The mold used for epoxy impregnating the coils will be redesigned to produce easy release, positive spacing, and flashless coils. A quantity of fully insulated coils using the redesigned mold will be fabricated for the acceptance tests. The types of tests will be determined in the development of the test plan. The uninsulated coils for this work will be Government furnished.

Development of Acceptance Tests. The application of conducting solutions or vacuum to detect cracks and pinholes will be investigated. Adequate testing procedures for screening coils for production will be determined. These will be derived from a series of visual, mechanical, and electrical tests including corona, breakdown, temperature cycling, and life tests.

The original Purchase Description is presented in Appendix A. Modifications to the contract are summarized in Appendix B. The modifications comprise evaluation of the magnet wire, extension of the life test to operate under full power conditions, redesign of the mold, develop acceptance tests, fab new coils and life test, design a skewed mold. The Test Plan is given in Appendix C.

II. PERCEPTION OF PROBLEM

The details of the design and construction of this particular lightweight generator are discussed in this section as they relate to proper performance of stator insulation. Examination of the wire used in the generator coils has revealed ridges and associated thinning of the wire insulation. These irregularities and their contribution to the observed failures are discussed.

The principal difficulty in devising a reliable compact stator insulation is that both the stator design and virtually every step of the conventional assembly process seem designed to thwart the use of any but bulky conventional insulation. Both mechanically and electrically, this service is very severe for a reliable but highly stressed insulation. Numerous detailed considerations affect the design and limit the choices of insulation systems and application processes. These are discussed in the following sections.

COIL FABRICATION

The individual stator coils are made from six layers of 0.040 by 0.200 inch copper magnet wire insulated with Pyre-ML, a polyimide based wire enamel. The coils are formed by hand with simple tooling. The process results in coils of not exactly the right shape, abrades the ML varnish, and potentially causes cracks in the varnish at points of maximum deformation. In addition, the coils must be flexed as they are installed in the stator.

The winding, roughly square in cross section after being formed, is wrapped with six layers of 0.0015 by 3/8 inch Kapton F tape. Each layer of tape is butt wrapped and fused. This system results in an extremely tough

and flexible insulation, but the application process inevitably traps small gas bubbles within the tape layers. These bubbles are the sites of insulation degradation in operation.

ASSEMBLY INTO STATOR

The stator has a three-phase lap winding, with 48 slots and eight poles. The coil-pitch is 67 percent of the pole-pitch. Then it follows that the coil-pitch is 4 (slots/coil), and the angle between the arms of a given coil is 30 degrees.

To assemble the coils in the stator, each coil is placed in position as shown in Figure 1. It is evident that each coil must be compressed to fit into the slot. This problem can be seen by recognizing that the slots converge; hence, the distance between slots is less at the top than at the bottom. The bending can cause the insulation to be damaged.

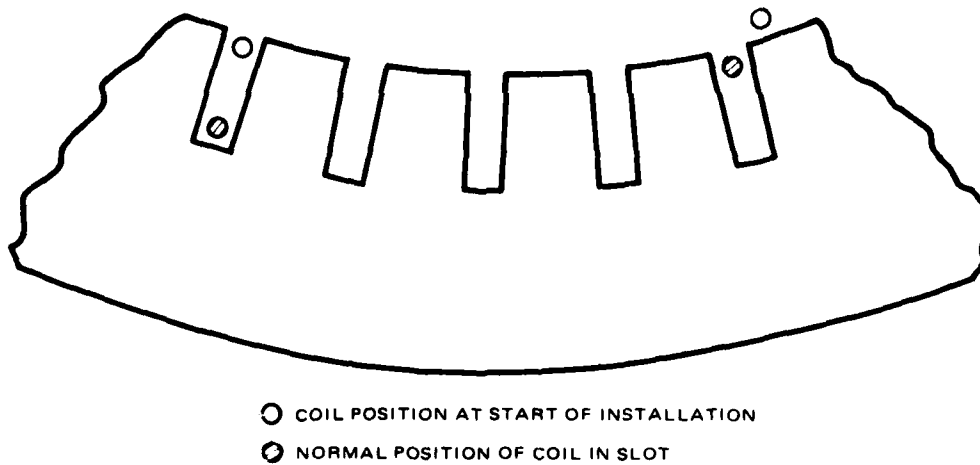
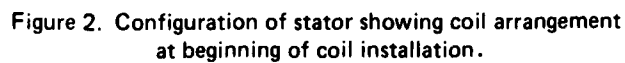


Figure 1. Section view showing coil is wider than slots.

The arrangement of the coils at the start of coil installation is shown in Figure 2. Each coil is placed in position in sequence, beginning with coil 1. One side of coil 1 is in slot 5 and the other in slot 1. The first four coils are called pitch coils. After coil 4, each slot is filled with two coils per slot. This condition continues through coil 44, which will be in slots 44 and 48.



The stator is constructed of punched laminations of a special high-strength steel. The edges of the stator slots are sharp and, because of the laminations, irregular along the length of the slot. The installation process consists of pounding the stator windings into the slots, usually with a mallet and wood or plastic block. A small wedge is driven in on top of the coil pair, to hold them in the slot. The small base of the stator compared to its length

adds to the other difficulties previously discussed. The result is that the stator winding insulation may be cut or damaged by the sharp irregular slots or compressed to less than its design thickness by the wedging.

THERMAL STRESS

Two thermomechanical stresses must be addressed in this intermittent service. The most obvious is the expansion mismatch between the stator and the copper in the coils. This mismatch has been observed to cause insulation creep in tape insulation over several cycles. The failure occurs at the ends of the windings near the point of egress from the stator and is caused by mechanical fatigue and separation of the tape wrap. In contrast to this isothermal effect, a thermal gradient through the insulation to the cooling fluid and stator is experienced during turn-on and is severest in a cold start. Of small consequence in a resilient insulation as presently used, this extreme gradient could cause failure in a rigid insulation because of the very large mechanical stresses it produces. Both the thermal gradient and the eventual hot spot temperature can be controlled by varying insulation thickness and coolant flow rate.

COIL TEMPERATURE RISE

An extremely important factor in the life of a highly stressed insulation is the actual operating temperature of the insulation. To be able to intelligently design a stator insulation, the designer must know average operating temperature, temperature gradient, and hot spot temperature. The calculation of these temperatures and gradients requires a detailed study of the transfer and dissipation of heat as the generator operates. The main transfer of heat from the stator coils is

1. Conduction through the insulation
2. Transfer across the insulation to oil interface
3. Transport of heat out of the winding slot by the oil.

Conduction through the insulation is the largest impedance in the heat transfer process. The ML coating on the wire is a significant contributor

to this impedance. A typical heavy ML coating on rectangular wire is 0.003 inch thick. The relatively poor thermal conductivity of the ML wire coating indicates that an alternate material or a thinner coating could be considered.

The transfer across the oil interface is affected by the shape and dimensions of the oil channel, the oil properties, and the temperature of the stator iron. Estimates of the power dissipation in the copper indicate an average insulation surface to oil temperature difference of 30°C.

When this value is added to the 100°C average oil temperature and the 38°C temperature drop estimated for epoxy impregnated glass, an average insulation temperature of 168°C is obtained at the ML coating surface. The 34°C drop across the ML coating results in an estimated maximum average insulation temperature of approximately 200°C and a hot spot temperature near 220°C.

While the above estimates are only approximate, they indicate high insulation temperature requirements and confirm that heat transfer is a critical design parameter for the insulation system.

THERMAL CONDUCTIVITY MEASUREMENT

As noted above, the thermal gradient and hot spot temperature can be controlled by varying the insulation thickness and coolant flow rate. Proper evaluation requires knowledge of the actual thermal conductivity of the insulation that can be ascertained from the heat flow through the insulation and the surface temperatures of the copper and insulation. The heat flow can be determined from the power dissipated in the copper by electrical currents if the heat flow is uniform across the area and the area can be defined. Alternatively, the total heat passing through the insulation during a measured interval can be determined with the coil immersed in a calorimeter. A dynamic method requiring more involved calculations consists of measuring the rate of temperature change of the copper given the weight and specific heat of the copper.

The necessary surface temperature measurements can be obtained readily with thermocouples; however, their use can locally disturb the flow

of heat transfer fluid sufficiently to change the temperature being measured. An effective way to measure the copper temperature is to use the copper as a resistance thermometer.

OIL COMPATIBILITY

It is well known that many insulating and lubricating fluids, particularly those with substantial additive content, may degrade solid electrical insulation. The lubricating oils presently used in the generator fall into this class. At the high temperatures involved, swelling and loss of strength in any susceptible solid insulation are greatly accelerated. The presently used Kapton insulation should not be attacked by these fluids, but any other materials used will require compatibility tests.

Lubricating oils qualified to Military Specifications MIL-L-7808 are composed of organic ester base stocks with additives to impart resistance to oxidation, corrosion, foaming, and to minimize wear. The base stocks are synthesized from organic acids esterified with di- and tri-hydric alcohols such as 2-ethyl hexyl alcohol, neopentyl glycol, or trimethylol propane. The additive materials are frequently proprietary but usually include tricresyl phosphate and a variety of organic amine compounds. The ester oils have higher solvency power than other aircraft fluids and cannot be used in systems designed for petroleum fluids, silicate esters, or silicones without serious deterioration of rubber parts, coatings, paints, and other organic materials. Hughes is generally aware of serious compatibility problems in turbine engines over the past few years. Apparently different formulations of di- and tri-esters with different additive packages may have grossly different effects on materials although the formulations are qualified to the military specifications. It appears probable, therefore, that the compatibility tests will have to be performed with a specific formulation of oil from a specified source.

FIELDS IN THE SLOT

Any electrical failure mechanism is driven by the electric field in the stator winding insulation; therefore, the first task is to find the operating

stress. If the slot is considered to be smooth-walled and uniform, the maximum field far from the ends of the stator can be found. Assuming that the overall wrap is uniform on all four sides and that two coils are 0.606 in. high, the thickness of allowed insulation and thus the peak fields are a function of the varnish thickness. These thicknesses are given in Table 1, and the instant impression is that these fields are quite large for this service.

TABLE 1. FIELD VERSUS VARNISH THICKNESS

ML Thickness, mils	Wrap Thickness, mils	Side Gaps, mils	Peak Field, V/mils
1.5	22	1.5	210.6
2.0	19	4	235.7
2.5	16	6.5	267.6
3.0	13	9	309.4
3.5	10	11.5	366.7

(The figure for "side gaps" is the oil cooling passage on either side of the winding.) These fields are nearly as large as the best reported average fields successfully achieved in a carefully prepared cast epoxy transformer insulation system intended for military service. Also they are substantially larger than the expected average operating fields for tape-wrapped insulations (typically below 100V/mil at this thickness).

An examination of the arrangement of stator insulation and cooling reveals that the coils are centered in the slot with small spacers of 0.007 inch Nomex wrapped around the sides and bottom of each coil. The bottom of the bottom coil in the slot is pressed firmly against the spacer and stator, while the sides of the coils are separated from the stator by about 10 mils of flowing coolant. If the resistivity of the coolant is high enough ($>10^6$ or $10^7 \Omega\text{-cm}$), it will act as extra insulation of very low breakdown strength. The top coil in the slot is separated from the bottom coil by twice the wrap and spacer. Thus, the bottom edge of the bottom coil experiences the highest stress, as shown in Figure 3.

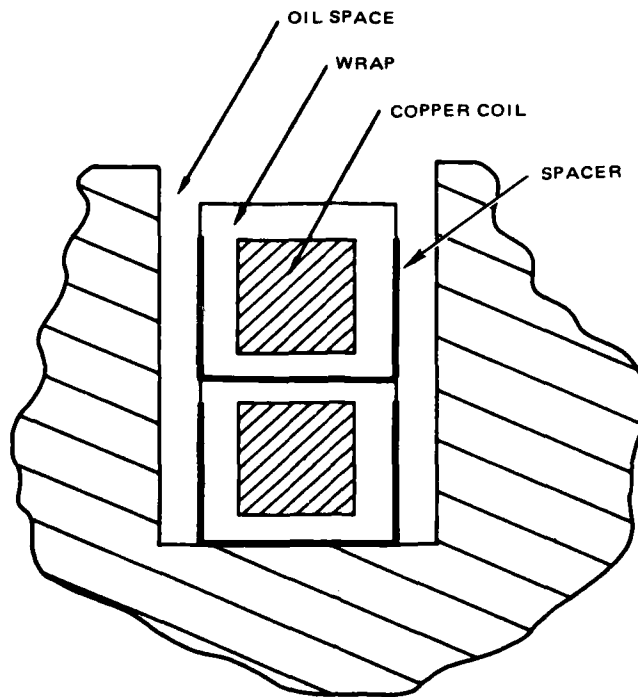


Figure 3. Typical slot showing coil and insulation.

CORONA IN INSULATION DEFECTS

The stator insulation is thick enough that the failure mechanism is most likely partial internal discharges (corona) in air pockets in the insulation. Tape-wrapped insulations are particularly susceptible to the trapping of large gas bubbles, which easily break down under high electrical stress.

It is easy to assess the size to which the gas-filled voids must be held to produce a corona-free insulation. By calculating the electric field in the void and then applying data taken from Paschen's curves and subsequent work, curves can be obtained that show stress applied across the insulation at breakdown versus void size. These curves, for flat and spherical voids, are shown in Figure 4. A flat void is typical of those found in tape-wound insulation (or capacitors). For an average stress of 300 V/mil, this void must be smaller than 10 μm to avoid breakdown. A spherical void is typical of a bubble found in a solid insulation. The maximum dimension of

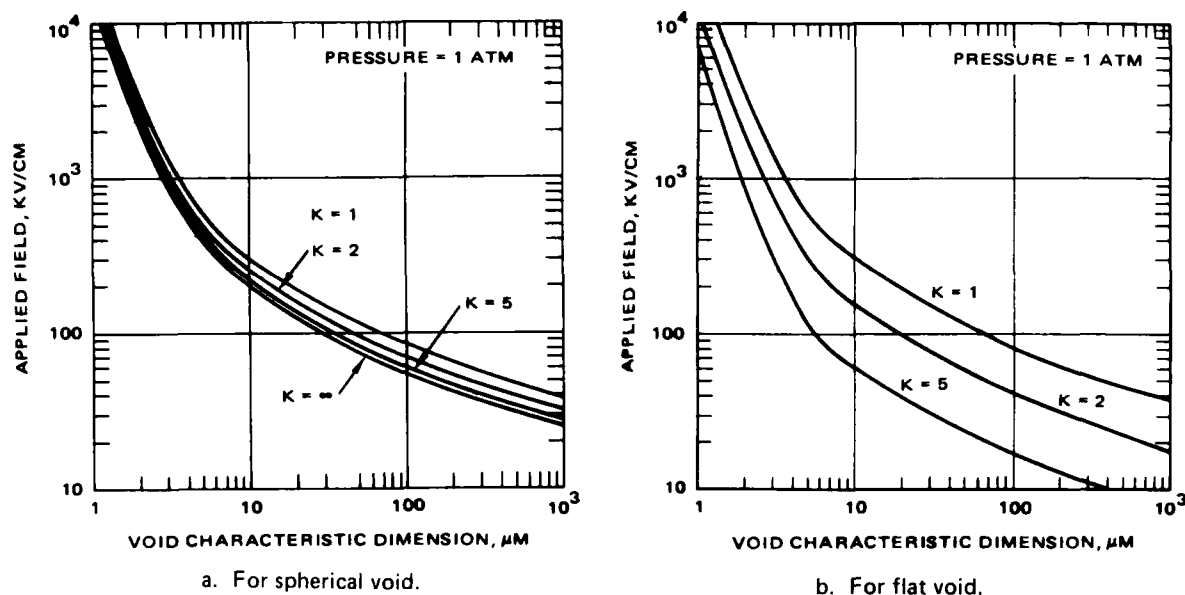


Figure 4. Corona inception stress over insulation versus void size for different dielectric constants.

this void is 20 μm. For the enhanced stress at the egress from the stator, these values drop to 8 μm for the flat void and 9 μm for the spherical void.

These data indicate that the stator insulation must be of extremely high quality, with few tiny voids, after installation in the stator, to enable corona-free (and thus long life) operation.

ELECTRICAL QUALITY OF COOLING OIL

The cooling oil is likely to be of dismal electrical quality, particularly for a 10-mil slot. The resistivity at 100°C is probably 10⁶ Ω-cm or below, and there will be a substantial distribution of conducting particles and bubbles since the oil is also used as a lubricant. Oil in this condition can have a breakdown strength of about 100 V/mil (DC), providing that no

conducting particle is larger than 15 percent of the slot width. Since the average field in the slot will be about 200 V/mil (peak), the oil will occasionally break down, throwing the entire voltage across the solid insulation. A good design might treat the oil in the slot as conductive.

TEMPERATURE

Insulation does less insulating and is more prone to failure at high temperatures than at low temperatures. The heat comes from three sources:

1. Copper loss
2. Ambient and coolant
3. Dielectric heating.

Uniform heating of a homogeneous dielectric produces a lower insulation resistance since insulation resistance decreases monotonically with increasing temperature. If the insulation resistance is low enough and the field high enough, current flowing through the insulation will cause significant heating and may result in thermal runaway.

Most dielectrics also contain thermally activated flaws. These are small volumes of dielectric (usually tens of mils on a side) in which the insulation resistance decreases much more rapidly than the surrounding material as temperature increases. Current then flows through the flaws, and insulation failure occurs because of localized thermal runaway.

Careful analysis of the actual operating temperatures and the thermal effects on both the electrical and physical properties of the insulation is vital to the selection of a suitable system for this severe service.

LIFE TEST EVALUATION

Evaluation of the test results by statistical or other means requires a realistic assessment of the actual service stresses that the insulation

system will see. The primary factors that bear on suitability of an insulation system for this application are summarized below:

1. High electric stress. This stress is well above the values typically used in electric machinery. It will force a reduction in the safety margins typically provided to compensate for occasional flaws or weak spots.
2. Short lifetime requirement. This requirement is short enough that, even at elevated temperatures, the usual chemical degradation processes that are the basis for most lifetime projections probably are not significant.
3. High rates of temperature change. These rates can induce cracking or separation that are sites for corona discharge or electrical breakdown.
4. High peak temperature. The peak temperature may not persist long enough to incur serious chemical degradation; however, electrical leakage currents at flaws may increase sufficiently to cause localized thermal runaway and breakdown.
5. Exposure to oil. Contact with a complex diester oil can be a problem because it is a continuous environment. Any degrading effects of the oil certainly will be accelerated at high operating temperatures.
6. Possibility of installation damage. The importance of physical damage at installation is considerable. This factor is difficult to estimate or simulate in a development effort and, even if detected by tests, it can be costly to rectify.
7. Mechanical operating stresses. Stresses of this nature are possible, if the coil is allowed to vibrate as the result of magnetic or mechanical forces. The damping effect of the oil may mitigate this type of stress if it should occur.

Tests to evaluate the life of an insulation system with regard to all of the above factors will be quite difficult.

Standard industry techniques for evaluating the life of insulation systems are based on extrapolating shorter term results, often obtained under accelerating test conditions, to long-term field use. These techniques are usually based on establishing a reaction rate factor under controlled conditions and displaying the life characteristics on log life versus the reciprocal of temperature plots. If the reaction rates do not change outside the conditions of measurement, extrapolations to longer time periods or increased stress can be made with reasonable accuracy. Usually statistical methods

are used to assess the probability of successfully projecting the results of sample tests to a larger portion of the population and to project the distribution of failure rate with respect to time.

The life of an insulation system for this application probably is dependent on freedom from flaws rather than thermally accelerated chemical reactions. Tests such as corona, dielectric withstanding, and high temperature insulation resistance will likely be better indicators of suitability than high temperature tests. An extended life test might provide no better indication of suitability than a 50 to 100-hour life test with properly selected before and after tests and careful attention to parameter changes.

COIL WIRE

The copper magnet wire for making the coils is manufactured by the Anaconda Company, Wire and Cable Division, 639 West Clay Avenue, Muskegon, Michigan 49440. The wire is insulated with Pyre-ML,* a polyimide-based wire enamel. According to DuPont, ML wire has the highest thermal properties of all the commercially available organic insulated magnet wires. ML is resistant to solvents, polymers, resins and generally used materials as evidenced by its exceptional compatibility with impregnating and encapsulating insulations. It has outstanding electrical properties with high dielectric and low loss characteristics at temperatures up to 220°C.

ML Coating

The Pyre-ML enamels are solutions of polyamic acids formed by the reaction of aromatic diamines with aromatic dianhydrides such as pyromellitic dianhydride. When the enamel is baked in the manufacture of the magnet wire, the enamel is converted to an inert polyimide.

Tests made according to AIEE Method 57 indicate that Pyre-ML coated wire has a thermal life of 20,000 hours at 243 degrees, as shown in Figure 5. Samples aged at 200°C and 220°C showed no failures after 40,000 hours.

*Pyre-ML is a registered trademark of the DuPont Company.

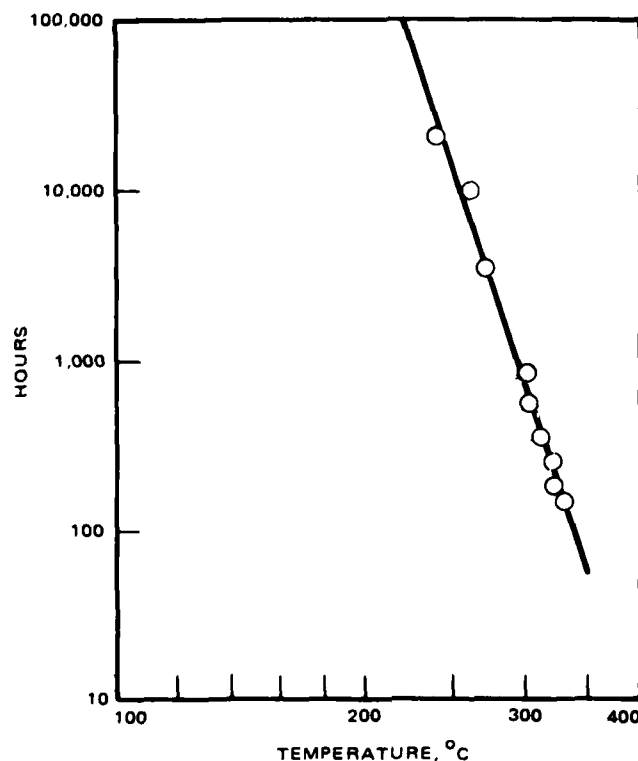


Figure 5. Thermal life unvarnished Pyre - ML coated wire.

Electrical and mechanical properties of magnet wire coated with Pyre-ML* are given in Table 2.

Wire Irregularities

The wire is rectangular copper insulated with heavy ML polyimide enamel. The wire dimensions are 0.040 inch thick by 0.200 inch wide. The rectangular cross section is formed from round wire by rolling. The large width-to-thickness ratio yields rounded edges as shown in Figure 6.

The 0.040 inch thickness is very near the lower limits of the Anaconda manufacturing capabilities and as such presents some peculiar problems related to thin cross sections in terms of processing. It is difficult to maintain a perfectly smooth contour with very thin cross sections. Small

*Pyre-ML Wire Enamel, Bulletin ML-19, E. I. DuPont De Nemours and Co. (Inc.), 1981.

TABLE 2. PROPERTIES OF MAGNET WIRE
COATED WITH PYRE-ML

Thermal Classification	220°C
Lifetime	20,000 hours at 243°C
Dissipation Factor, 100 Hz	0.25 at 25°C 10.0 at 200°C
Dielectric Constant	3.66 at 25°C 3.63 at 200°C
Coefficient of Thermal Expansion	$4 \times 10^{-5}/^{\circ}\text{C}$
Coefficient of Thermal Conductivity	$35 \times 10^{-5} \text{ cal/sec/cm}^2/^{\circ}\text{C/cm}$
Dielectric Strength	3400 V/mil
Heat Shock	425°C

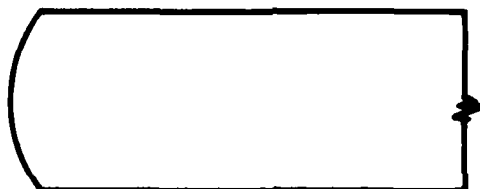


Figure 6. Section of wire with rounded edges.

projections on the wire at critical places enhance the field and aid breakdown. Furthermore, the ML coating is thinner over the projections as noted in Figure 7, a metallographic cross section of ML enameled magnet wires. In this case, the insulation thickness is 1.1 mils for the flat portion of the wire and is 0.6 mil for the curved side. Over the projection, where the curved side joins the flat side, the insulation thickness is barely 0.1 mil. It is evident that the ML coating adheres extremely well, and no observable cracks or breaks are in the insulation. Where the coil is bent sharply, the insulation coating is thinned but still appears to adhere to the copper.

The asperity of the wire will decrease the reliability and lifetime. In discussing the problem with Anaconda, they indicated that the copper projections are not considered a normal commercial condition, although

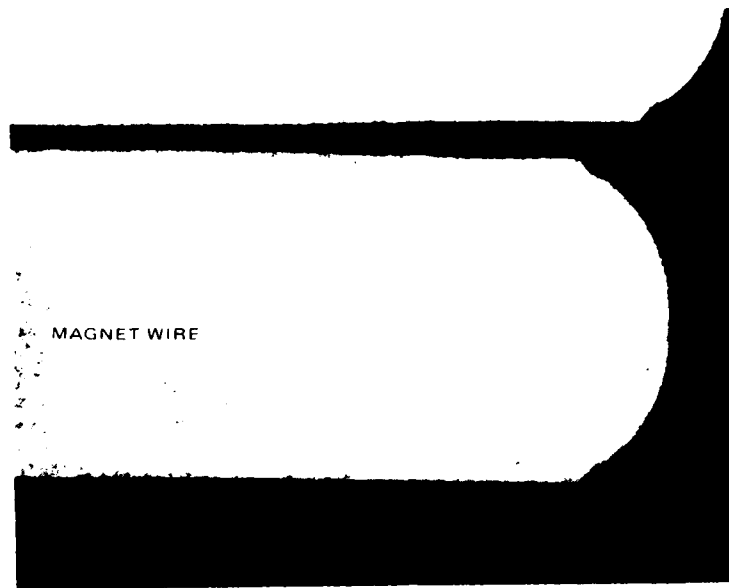


Figure 7. Metallographic cross section of ML magnet wire.
(Magnification 75X)

these conditions do occur, particularly with very thin cross sections. However, Anaconda is confident that the conductor condition with respect to corners could be improved by further processing.*

HUGHES APPROACH

The present coils are fabricated from ML coated rectangular magnet wire wrapped with several layers of Kapton tape. Kapton is attractive because it has excellent temperature endurance and good heat conductivity. It is compatible with the cooling oil, and is highly resistant to corona. A schematic diagram of a tape wrapped coil cross section is shown in Figure 8. As shown, the Kapton tape tends to form a space between turns. In the stator, a space between the coil and slot allows oil to circulate for cooling. It also provides some electrical insulation. As the oil circulates, some of the air under the tape is displaced. Some air bubbles remain that can lead to corona discharge along the edge of the coil.

*Lee R. Balkema, private communication.

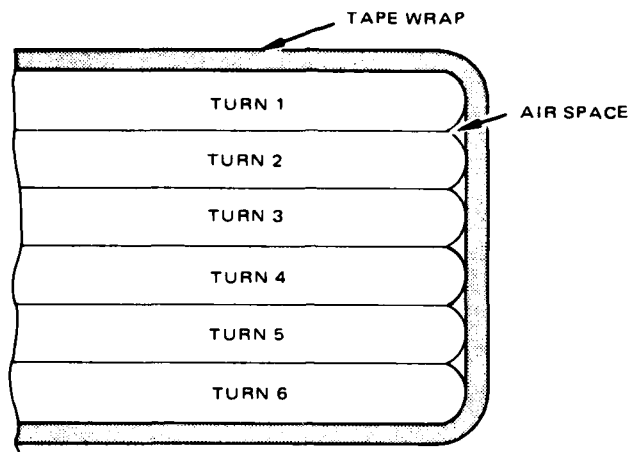


Figure 8. Tape wrapped coil edge structure.

Hughes approach to a void free insulation is to use a resin impregnated system. There are a moderately large number of possible insulation systems that might be suitable. In the following sections some of the most promising materials are examined.

III. MATERIAL SELECTION

The design, construction, and installation of this stator insulation system is a technically complex and challenging problem. The Bendix machine is a significant achievement in size and weight reduction, but its design and manufacture place extremely severe requirements on the stator insulation. The ideal result of this program would be an insulation system that could be used in the present manufacturing environment with no change in any other process. Otherwise, the ideal solution would be to supply the generator manufacturer with completely fabricated stator windings for "drop-in" use.

A highly-stressed stator insulation can be designed in two ways. The simplest is to design a replacement for the presently used Kapton tape, containing the field in the stator slot as presently done. The second method is to devise an insulation that uses a ground-plane on its surface to contain the electric field entirely within the solid insulations. This technique allows the precise control of peak and average fields, avoids the electric field in the flowing coolant, and removes the objections about electric field enhancement at stator slot irregularities and at coil ingress and egress. Field control is discussed separately in this section, since the insulation system requirements for either technique are similar.

FIELD CONTROL

If the peak field is several times larger than the average field, the insulation is usually designed everywhere to withstand the peak value. This makes the insulation heavy and bulky. The size and weight can be reduced by reducing the ratio of peak to average field. Various field control

techniques are used. The principal thrust is to reduce the peak field at asperities by providing a surface of larger radius of curvature to stand the field.

The most practical form of field control for the stator windings that does not involve stator modification is to use a ground plane on the surface of the solid insulation to contain the field in the insulation, as shown in Figure 9.

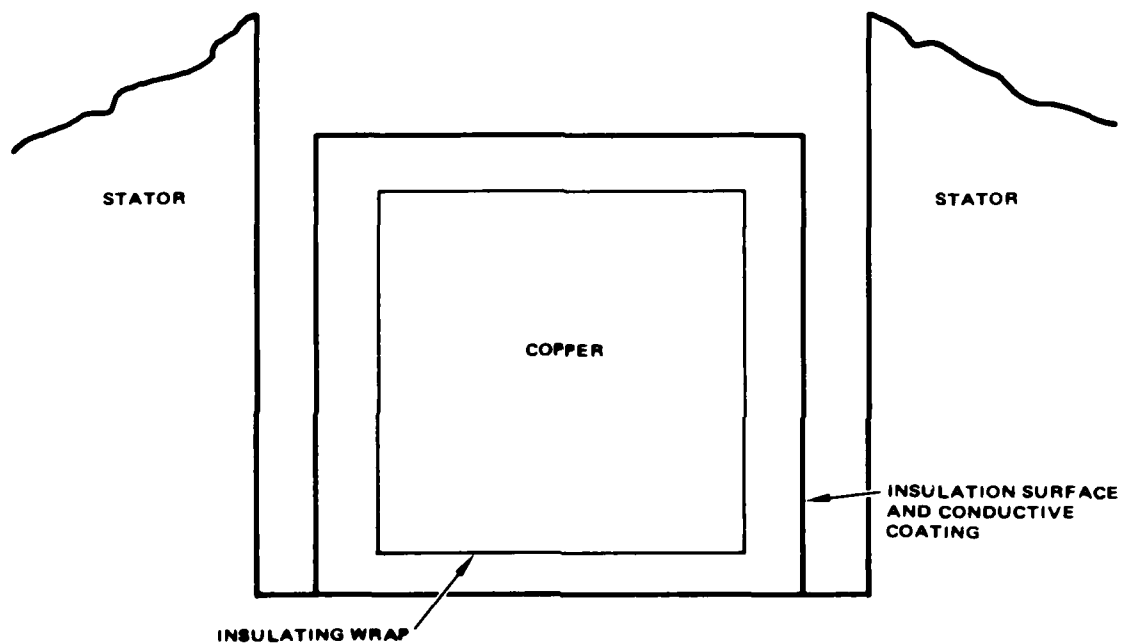


Figure 9. Placement of ground plane to contain field in insulating wrap.

The outer surface of the insulation is smooth and can be made to have a large radius of curvature at the point where it exits the stator, so the peak to average field ratio will be 1, rather than 2 or 3. The ground plane coating can be a thin vacuum deposited layer of aluminum or a thicker epoxy-silver layer. At places where the copper conductor must terminate, small field control shields shown in Figure 10 are used, to avoid the sharp edge at the end of the ground plane.

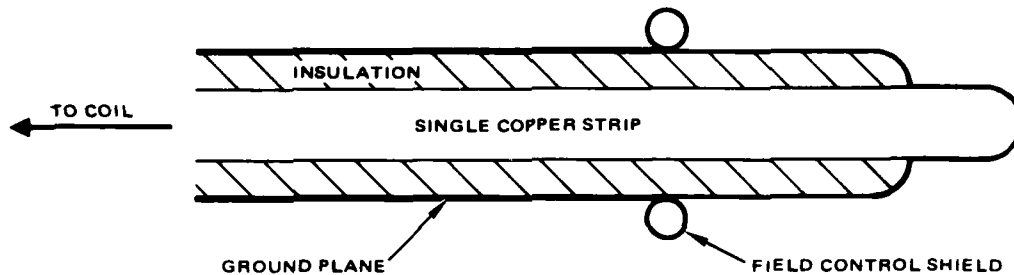


Figure 10. Termination of coil lead showing field control shield, cross section.

If this type of field control is used, additional advantages can be exploited to increase reliability. First, the interphase fields and, therefore, failures in the stator end bays are greatly reduced, since the only place fields are present is between the termination point and ground. Also, if the ground plane is used, corona tests could be performed on the stator windings before assembly into the stator, to weed out defective windings.

COIL CONSTRUCTION

Presently used insulation systems employ a heavy (2 to 3 mil) enamel coating on the bars and a symmetrical wrapper, even though the fields are not the same on all sides of the coils. From the severity of the problem, and from the field data, it could be concluded that a more engineered approach is necessary. This approach could include coils preformed to the necessary angles and thinner varnish coating.

Coil preforming could be improved. A more highly engineered forming fixture would produce coils the right shape for easiest insertion. The whole object of this step is to reduce insulation damage during installation of the winding.

The present varnish coat is too thick for any electrical purpose, so it must be for mechanical cushioning during forming. Better forming eliminates this need, and reduction of the varnish thickness to 1 mil eliminates unneeded bulk without sacrificing any necessary electrical properties.

THERMAL

The maximum insulation temperature is quite sensitive to insulation thickness and thermal conductivity. The insulation candidates differ substantially in their thermal conductivity. If the designer chooses a material with a higher thermal conductivity, he can use a thicker insulation to reduce electric stress or allow the material to have a lower temperature tolerance. Therefore, the thermal transfer properties of the insulation system must be balanced with the desire for maximum thickness for electrical strength and the temperature tolerance of the material.

INSULATION MATERIAL REQUIREMENTS

The general requirements for candidate materials are

1. Tough outer layer
2. Slight flexibility
3. Freedom from voids when installed
4. Mechanical strength
5. High service temperature
6. Resistance to rapid temperature changes.

The insulation must operate in the 250 to 400 V/mil (peak) range electric field. This field range, and the allowable void size, argue for some type of impregnated system, either liquid or resin.

The most important specific requirements for the insulation material are summarized in Table 3. It is evident that the combination of requirements is extreme. The operating temperature for the coils is 200°C with an inlet oil temperature of 100°C. The voltages are 6000 volts between coils and 3500 volts between coil and stator. Finally, the oil is highly corrosive to many materials.

SELECTION FACTORS

An important aspect of the program was to select the dielectric for the insulation system. Several candidate materials of interest seemed to be suitable and should be evaluated. In addition, other materials were sought

TABLE 3. INSULATION MATERIAL REQUIREMENTS

Characteristics	Requirements
Encapsulant	Must adhere to ML enameled rectangular copper wire
Coil Temperature	Average temperature, 200°C Hot spot temperature, 220°C
Oil Compatibility	MIL-G-7808, synthetic lubricating oil, composed of organic esters with tricresyl phosphate and organic amine additives.
Phase Voltage, line-to-neutral	3500 V RMS
Phase-to-Phase Voltage	6000 V RMS
Life	50 hours at full load intermittent duty Design goal 250 hours continuous
Coil Installation	Twisting and severe bending of pitch coils

as possible candidates. Then the most likely materials were screened by using test models to evaluate their suitability for stator coils.

Some of the requirements for the insulation material (e.g. mechanical strength and lifetime) have been discussed in the above sections. To compare candidate materials, additional factors should be considered. These include temperature endurance, processing complexity, thermal properties, costs, and availability. For ease of comparing the different candidate materials, the important factors and requirements for the insulation system are given in Table 4. Based on these requirements, the following types of material were considered as candidate dielectrics.

<u>Class</u>	<u>Specific Types</u>
Polyimides	Kapton, ML Varnish
Fluorocarbons	Teflon, Viton
Polysulfides	Polyphenylene Sulfides
Silicones	Silgard Resins
Epoxyes	Scotchcasts, Epon

TABLE 4. SELECTION FACTORS
AND REQUIREMENTS

Selection Factors	Requirements
Temperature Endurance	250 hours at 200°C
Compatibility with Oil	Must be resistant to oil at high temperature
Process Complexity	Practicable processing and minimal development
Thermal Properties	High thermal conductivity Low thermal expansion
Mechanical Properties	Must be strong, tough, slightly flexible and adhere to polyimide
Electrical Properties	High electrical strength
Costs	Preferably low or moderate
Availability	Only commercial materials

A careful survey of the literature and inquiries with vendors was conducted to determine likely candidate dielectrics for the insulation system. Those materials that looked promising were reviewed against the selection factors given in Table 4 as a criterion; the best are presented in Table 5. The data for each dielectric are listed according to the selection factors for easy comparison and selection. These materials are all commercially available.

CANDIDATE DIELECTRICS

The number of candidate materials is severely limited by the combination of requirements. Although the most promising materials are given in Table 5, most are unsatisfactory. The prime candidate dielectrics are

1. Pyre ML varnish
2. Molded epoxy and polyweb
3. Molded epoxy and glass.

TABLE 5. COMPARISON OF CANDIDATE MATERIALS
VERSUS SELECTION FACTORS

SELECTION FACTORS	SYLGARD 184	730 RTV FLUOROSILICONE	POLYPHENYLENE SULFIDES	KAPTON F	KAPTON	PYRE ML	GE 707 POLYESTER	TEFLON 100 FEP	SCOTCHCAST 280	EPON 825
TEMPERATURE ENDURANCE	200°C	260°C	260°C	200°C	300°C	300°C	200°C	275°C	200°C	165°C
OIL COMPATIBILITY	FAIR	VERY GOOD		EXCELLENT	EXCELLENT	EXCELLENT	GOOD	VERY GOOD		GOOD
PROCESS COMPLEXITY	VAC IMPREG	VAC IMPREG	FLUIDIZED BED	WRAP	WRAP		VAC IMPREG	FLUIDIZED BED	VAC IMPREG	VAC IMPREG
THERMAL PROPERTIES										
α IN IN/°C	300×10^{-6}		12×10^{-6}	20×10^{-6}	20×10^{-6}	40×10^{-6}	50×10^{-6}	90×10^{-6}	150×10^{-6}	68×10^{-6}
K, CAL/CMSEC °C	3.5×10^{-4}				4.26×10^{-4}	3.5×10^{-4}		4.65×10^{-4}	12×10^{-4}	5×10^{-4}
MECHANICAL PROPERTIES										
TENSILE STRENGTH, psi	9000	3000	16200	9000	30000	15000	8000	3000	7000	9000
FLEXURAL STRENGTH, psi			26000				11500		1235	17800
ADHESION, psi	15	15			6	6	GOOD			GOOD
HARDNESS	35 SHORE A								75 SHORE D	82 SHORE D
ELONGATION, percent	100	175	1	20	25	15-20		70		2.9
ELECTRICAL PROPERTIES										
ELECT STRENGTH V./mil	600	331	450	4200	4000	3000	1900	6500	356	400
COST	LOW	MODERATE	LOW	MODERATE	MODERATE		LOW	MODERATE	LOW	LOW

The unsatisfactory materials that will not be investigated further are

1. Sylgard 184
Oil compatibility
Large thermal expansion
Large percentage of elongation
2. 730 RTV
Large percentage of elongation
Low volts/mil
3. Polyphenylene Sulfides
Processing complexity
Inflexible
4. Teflon 100 FEP
Processing complexity
5. Scotchcast 280
Large thermal expansion
Low volts/mil

Based on Hughes experience, epoxies are the most attractive materials for this application. Hughes has used bisphenol A type epoxies with proprietary hardener systems for many high voltage components.

Two reinforcing systems have been used for high voltage applications: glass cloth and polyester web. The latter is widely used in highly stressed regions of solid encapsulated transformers. It is flexible and easy to work but is weaker than glass; the coefficient of thermal expansion of the composite material is high, about 60 percent of epoxy alone.

Glass cloth, an extremely strong reinforcer, has been used for overwrapping capacitors which need it to survive temperature cycling. It has the further advantage of a low coefficient of thermal expansion, so that when combined with epoxy the thermal expansion coefficient can be made to closely match copper. One weakness of the glass reinforcement is the possibility of microcracking along the fibers due to the mismatch of Young's moduli.

During the evaluation, a polyesterimide varnish, GE 707, was thought to be a suitable dielectric and it was examined. For comparison, it has been added to the list of materials presented in Table 5.

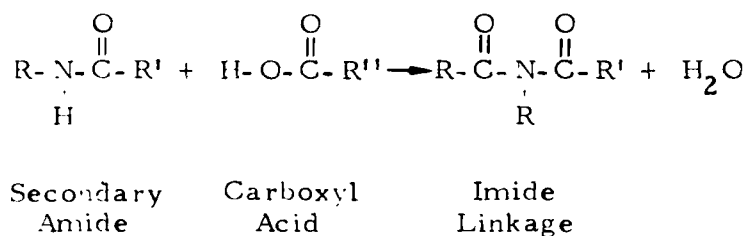
EVALUATION OF CANDIDATE DIELECTRICS

To evaluate candidate dielectrics, straight 6-inch long segments were fabricated with ML wire. Each model consisted of either two or six layers of 0.040 by 0.200 inch ML wire similar to the straight portion of a stator coil. Lengths were 4 to 8 inches.

Examination of Means of Processing

Pyre ML. This polyimide based coating, manufactured by DuPont, is supplied in solution of N-methylpyrrolidone (NMP) at roughly 14-17 percent solids. The cured resin has a film tensile strength of 15,000 to 20,000 psi and elongation of 15-20 percent. The cured material has a less than desirable arc resistance because the resin tends to carbon track when used in high voltage applications. The resin has lower average electrical properties at room temperature but exhibits exceptionally good electrical properties at elevated temperatures.

The disadvantages of the polyimide resins for this application are their curing mechanism and high solvent content. The curing reaction is



where water is generated as a byproduct. The water causes voids in cures of thick films. To prevent voids by solvent evaporation, a high temperature step cure is required in thin films.

To determine if a void-free coating could be obtained, single strands of Pyre-ML rectangular coated wire, 0.040 x 0.200 inch, were dip-coated with Pyre-ML enamel. The enamel was first diluted to 3 to 4 percent solids. The dip coat was prebaked for 30 minutes at 150°C and post-baked for 1 hour at 250°C. Ten to twelve coats were required to obtain a film thickness of 1 mil. Good quality coatings free of voids were obtained. Thicker coatings can be made by repeating the process.

Next, six-layer wire samples were used. A total of 30 coats (2 to 3 mils) was applied. Examination showed poor adhesion between layers due to many bubbles. The bubbles were formed when the solvent could not escape during curing. It was concluded Pyre-ML enamel cannot be used for encapsulating coils.

GE 707 Varnish. GE 707 is a semi-rigid solventless, two-part polyesterimide varnish manufactured by General Electric. It is designed for dipping and vacuum pressure impregnation of electrical equipment.

There were two areas of concern: (1) would it be resistant to synthetic oil at 200°C, and (2) would it be flexible enough for installation. Resistance to the attack by synthetic oil was determined by immersing several components in the oil for 250 hours at 200°C and measuring volume swell. Tests showed no measurable change in volume with only a slight

discoloration of the resin surface. The flexibility was determined by measuring three point loading flexure per ASTM D790 method 1. The results are presented in Table 6. The data are the average of three samples.

TABLE 6. PROPERTIES OF EPON 825/HV and G. E. 707

Resin	Temperature, °C	Flexural Strength, psi	Modulus of Elasticity, psi
GE 707	21	11,500	530,000
	49	12,800	410,000
	82	3,100	110,000
Epon 825/HV	21	17,800	510,000
	49	20,700	470,000
	82	17,100	460,000

The data indicate that the GE 707 is sufficiently flexible to meet the bending required during installation of the pitch coils. It is more flexible at elevated temperatures.

A single 6-inch strand of ML wire dip-coated with GE 707 and cured at 170°C for 30 minutes gave a void-free coating. Attempts to encapsulate both two-layer and six-layer samples were unsuccessful because of voids that formed during curing between layers. It was concluded that GE 707 cannot be used for encapsulating coils.

Epon 825/HV Hardener. This resin system is an amine cure of a diglycidyl ether of bisphenol A resin. The Epon 825 resin is manufactured by Shell. Hughes developed the HV hardener system to encapsulate high voltage components. This amine system consists of methane diamine, metaphenylene diamine, and benzyl dimethylamine.

The flexure data for Epon 825/HV are shown in Table 6. The data indicate that the system is marginal to meet the bending required for assembling the coils. The flexural properties show little change over the temperature range. Oil immersion tests showed no evidence of swelling after 250 hours at 200°C.

This epoxy system appears to be adequate in every respect except it may not be flexible enough. A possible solution to the problem might be to "B" stage the resin. Thus the encapsulated coils will be only partially cured before installation in the stator. At this "B" stage of cure, the epoxy would be more flexible and the coils could be installed without breaking. After installation, they could be cured to completion.

The scheme was evaluated using specimens made with six layers of ML wire. The outside of the wire was wrapped with two layers of glass cloth, 4 mils thick, placed in a mold and impregnated. The parts were cured for 2-1/2 hours at 66°C.

Flexibility tests of the encapsulated wires were run at 0, 24, and 49°C by bending the coil 20° and straightening. The results are given below:

- 0°C - cracks with delaminations
- 24°C - cracks at stress points, no delaminations
- 49°C - no cracks or delaminations

By heating the parts to 24°C for several hours, the cracks and delaminations healed.

It is concluded that, if necessary, the coils could be "B" staged and would be flexible enough to install in the stator without cracking. The processing is more elaborate than normal encapsulation, but it could be used satisfactorily.

Construction of Test Samples

Test pieces consisted of segments of ML wire several inches long. Samples were mostly two or six layers of wire overwrapped with one or two layers of dielectric tape. Then each assembly was impregnated with Epon 825 epoxy/HV hardener system. The two-layer designs were used initially because of their simplicity. The six-layer samples corresponded to the straight portions of the coils and were simple to fabricate. The thickness of the dielectric was about 12 mils on the outside of the six-layer samples and about 1.9 mils between layers. The straight wire test samples are summarized in Table 7. Epoxy/glass refers to Epon 825/HV hardener and Volan A glass cloth. Polyweb refers to porous polyester mat made by 3M Company.

TABLE 7. CONSTRUCTION OF STRAIGHT WIRE TEST SAMPLES

Sample Number	Layers of Wire	Length, Inches	Dielectric System
1	Two	4	Epoxy/glass
2-9	Two	8	Epoxy/glass
10, 11, 14	One	6	GE 707
12, 13, 15, 17	One	8	GE 707/glass
18	Six	8	Epoxy/glass, "B" staged
1-19	Six	9	Epoxy/glass
20, 21	Six	9	Epoxy/polyweb
22, 23	Six	9	Epoxy/glass

Electrical Tests

Corona inception voltage (CIV) and corona extinction voltage (CEV) measurements of epoxy/glass, polyester/glass, and polyester specimens were conducted in freon and air. The results indicated that the CIV in freon is >3 kV for a two-layer epoxy/glass segment. The CIV in air is about 1 kV. Breakdown occurred in air at the ends. Examination showed that there was no polyimide coating at the point of breakdown, and the epoxy was extremely thin. These measurements were the equivalent of turn-to-turn in a coil and were promising. The CIV for GE 707 polyester/glass and polyester were about 0.5 kV.

New samples were prepared with the ends carefully rounded. In addition, the ends were staggered to separate the test lead connections, which improved the CIV. Vacuum impregnation with freon further increased the CIV.

The CIV for six-layer segments using polyweb and glass cloth impregnated with Epon 825/HV hardener are compared in Table 8. As noted, the glass cloth samples are somewhat better than the polyweb. The thermal conductivity for samples made with glass are better too, as shown in Table 9.

TABLE 8. CIV BETWEEN LAYERS FOR SIX-LAYER
STRAIGHT SEGMENTS

Sample Number	Layers	Insulation	CIV, kV	CEV, kV
20	One to two	Epoxy/ Polyweb	>4.0	3.70
	Two to three		>4.0	
	Three to four		3.92	
	Four to five		>4.0	
	Five to six		1.29	
21	One to two	Epoxy/ Polyweb	>4.0	1.67
	Two to three		1.98	
	Three to four		1.87	
	Four to five		2.23	
	Five to six		3.61	
22	One to two	Epoxy/ Glass	>4.0	3.49
	Two to three		>4.0	
	Three to four		>4.0	
	Four to five		>4.0	
	Five to six		3.82	
23	One to two	Epoxy/ Glass	>4.0	3.0
	Two to three		>4.0	
	Three to four		>4.0	
	Four to five		3.2	
	Five to six		>4.0	

TABLE 9. THERMAL CONDUCTIVITY OF STATOR COIL INSULATION SYSTEMS

Specimen	t, in.	ΔT , °C	ΔP , watts	G, °C/watt	k, BTU hr ⁻¹ ft ⁻¹ °F ⁻¹
ML	0.001	0.75	28	0.027 ± 0.012	0.11
Polyweb	0.021	22	30	0.726 ± 0.007	0.13
Glass Cloth	0.017	11	29	0.368 ± 0.008	0.19
Glass Tape	0.012	8	29	0.280 ± 0.006	0.19

The measurements simulate turn-to-turn tests. The results are very satisfactory to meet the 100 volt requirement. The test results are indicative of the capability of the epoxy/glass insulation system and suggest that this system will be adequate to meet the generator requirements.

A fixture for testing straight segments in slots is shown in Figure 11. Drawing No. 3707721 of this fixture is given in Appendix D. The CIV coil-to-slot for the specimens shown in Table 7 are given in Table 10. The lower values are attributed to air bubbles in the freon and deficiencies in the impregnation.

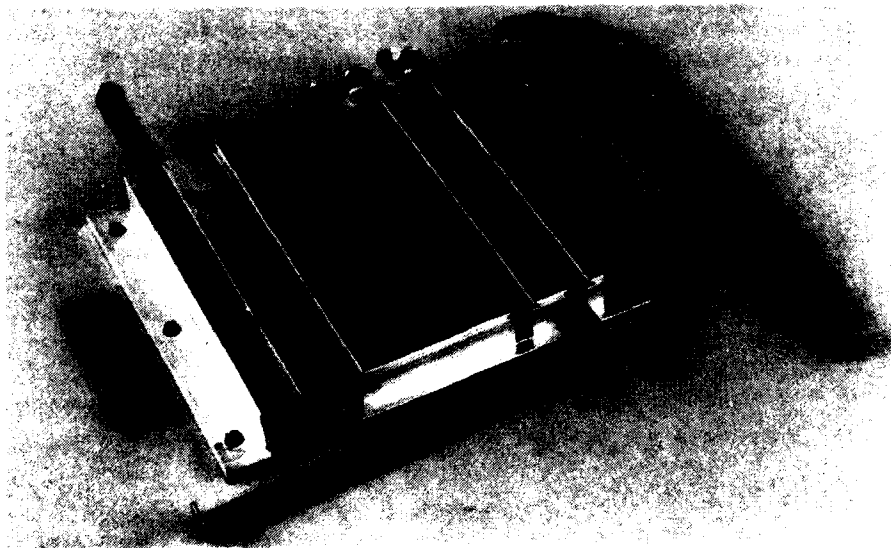


Figure 11. Slot simulator test fixture with slot covers and test samples.

TABLE 10. CIV FOR SIX-LAYER STRAIGHT SEGMENTS
USING SLOT SIMULATOR

Sample Number	Insulation	CIV, kV	CEV, kV
20	Polyweb	0.70	0.52
21	Polyweb	1.01	0.85
22	Glass	3.83	3.44
23	Glass	2.31	2.11

Preliminary measurements of breakdown voltage for two of the above samples are given in Table 11. The epoxy/glass and epoxy/polyweb insulation both exhibit adequate breakdown voltage.

TABLE 11. BREAKDOWN VOLTAGE FOR EPOXY DIELECTRIC

Item	Dielectric	Turns	Breakdown	
			kV	V/mil
Straight Segment, No. 20	Epoxy/Polyweb	Four to five	5.7	1583
		Five to six	5.6	1556
		One to ground	6.8 top	567
		Three to ground	8.8 side	1100
Straight Segment, No. 23	Epoxy/glass	Two to three	4.7	1567
		Four to five	6.0	2000
		One to ground	14.8 top	673
		Six to ground	17.4 side	1160
Prototype Coil, S/N 5	Epoxy/glass 1 layer 7 mil glass tape	Left side-ground	7.6	506
		Right side-ground	8.5	567

Oil Compatibility

Three separate tests were conducted to assess compatibility of Epon 825/HV hardener in MIL-L-7808 oil for prolonged periods at elevated temperatures. Initially, the change in CIV versus hours at 200°C for six-layer samples was measured. Secondly, it was thought that volume resistivity might be a more sensitive test. Thirdly, physical properties were measured for epoxy/glass laminate soaked in the oil at elevated temperatures for 250 hours.

CIV. The change in CIV for six-layer segments immersed in oil at 200°C for 97 hours is given in Table 12. "Shorted" turns were measured by painting a conductive silver coating on the outside of the sample, connecting the six layers of wire together, and applying voltage between the conductive coating and the wires. This condition approximates a coil in the stator slot. The data indicated that some change may occur between turns; however, it does not appear to be significant since the CIV is much greater than needed. The results for the shorted turns did not show evidence of any degradation. The parts exhibited darkening with increasing temperature and time. Otherwise, the appearance of the material did not change.

Volume Resistivity. Two-layer and six-layer segments were immersed in oil for up to 288 hours at 170 and 200°C. The outside surface of the samples was painted with a conductive silver coating. A Beckman megohmmeter was used to measure the resistance of the epoxy/glass. The voltage was set to 500 V, and a reading taken after 1 minute. Typical values were 10^{13} ohms range. The volume-resistivity, ρ , in ohm-cm was calculated from the resistance measurement using Equation (1)

$$\rho = R \times \frac{A}{t} \quad (1)$$

where A is the area and t the thickness. For all samples $t = 0.020$ in. (0.051 cm). The area for the two-layer samples was 3.61 cm^2 . For six-layer samples S/N 3, 4, 5, the area was 22.7 cm^2 ; for S/N 20, 21, 22, 23, the area was 5.68 cm^2 . The data are given in Table 13.

TABLE 12. EFFECT OF OIL AT 200°C ON
EPOXY/GLASS DIELECTRIC

Sample Number	Turns	CIV, kV				
		Hours				
		0	25	49	73	97
3	One to two	0.85	2.7			1.3
	Two to three	0.98	1.32	3.69	2.36	1.58
	Three to four	1.28	1.18	1.18	1.31	0.85
	Four to five	0.85	1.00	2.82	2.81	1.16
	Five to six	2.05	1.24	2.38	1.56	0.97
	Shorted		2.47	0.78	6.84	>4.0
4	One to two	1.86	1.27	1.05	1.83	1.13
	Two to three	1.48	1.74	1.05	1.39	1.13
	Three to four	1.65	1.37	1.09	1.30	0.87
	Four to five	2.29	1.73	1.19	1.12	1.04
	Five to six	1.55	1.12	1.35	1.23	0.98
	Shorted		2.28	2.65	2.48	2.81
5	One to two		3.3	1.53	1.48	1.05
	Two to three		2.56	1.57	1.67	1.84
	Three to four		2.51	1.28	1.42	1.07
	Four to five		2.55	1.47	1.68	1.57
	Five to six		1.31	1.40	1.07	
	Shorted		1.86	2.57	3.73	3.67

TABLE 13. CHANGE IN VOLUME-RESISTIVITY FOR EPOXY/GLASS
DIELECTRIC AFTER PROLONGED EXPOSURE TO OIL
AT 170 AND 200 °C

Sample Number	Volume Resistivity, 10^{15} ohm-cm Two-layer Segments, 170°C										
	Hours										
	0	24	50	74	97	147	164	188	238	264	288
2	2.5		6.4				5.3				2.8
	1.4		3.5				5.0				2.5
6	0.39		4.2				8.5				2.1
	2.5		7.1				5.0				
7	3.5		2.8				1.4				3.5
	0.74		2.3				1.8				2.1
8	5.3		4.2				1.1				2.0
	2.1		5.0				1.8				1.1
9	5.3		2.8				1.1			1.4	1.4
	<u>4.2</u>		<u>2.5</u>				<u>2.8</u>			<u>2.1</u>	<u>1.9</u>
Average	2.8		4.1				3.4			1.8	2.2
Six-layer segments, 200°C											
3					2.2	4.5			4.5		
					3.3	2.8			4.5		
4					2.8	3.3			2.0		
					3.8	2.2			4.5		
5					2.8	4.5			6.7		
					<u>2.0</u>	<u>2.8</u>			<u>3.9</u>		
Average					2.8	3.4			4.4		
20		7.2		3.36				2.68			2.24
21		4.0		2.24				1.44			1.24
22		4.0		2.0				1.32			1.32
23		<u>3.6</u>		<u>1.8</u>				<u>0.88</u>			<u>1.16</u>
Average		4.8		2.36				1.60			1.48

The changes in resistance are not significant. The experimental errors are large, and the variations are well within the experimental errors. It is concluded that the epoxy/glass, after 288 hours in 200°C oil, did not show evidence of degradation.

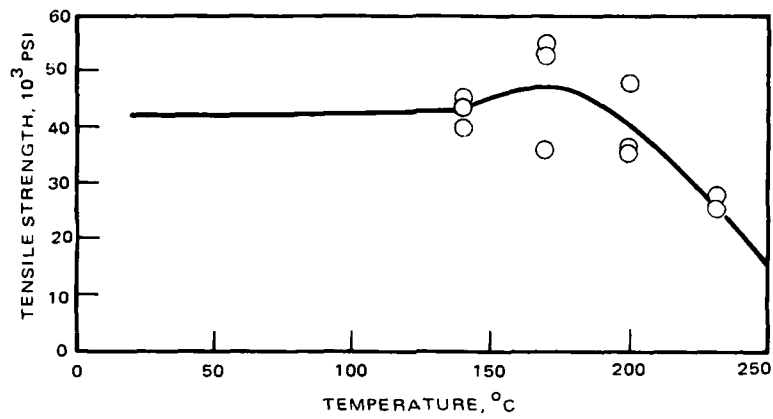
Tensile Strength. To make the tensile specimens a single sheet of epoxy/glass was made. The construction and proportions of glass and epoxy were similar to that used for the coils. The original piece was 8 x 9 x 0.050 inches. It was cut into 12 pieces, 3/4 inches wide. The pieces were immersed in oil and heated to 140, 170, 200, and 230°C for 250 hours. There were three samples at each temperature. The specimens got progressively darker with increasing temperatures. Otherwise, the appearance of the parts did not change visibly. The tensile strength, modulus of elasticity, and percent elongation was measured for each sample. The data are plotted in Figure 12. As noted, all three physical properties increase slightly at about 170°C. This increase is attributed to additional crosslinking. The point at which the properties start to degrade is around 195°C. The hardness of the samples after exposure at 140, 170 and 200°C was 75 Shore D. The 230°C sample measured 67 Shore D.

It is concluded that the epoxy/glass is compatible with the oil. It should be safe to operate at temperatures up to 190°C for at least 250 hours.

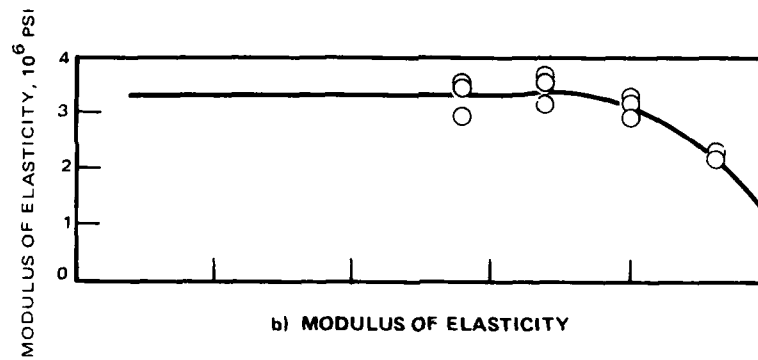
INSULATION SYSTEM SELECTED

The prime candidate dielectrics were Pyre-ML polyimide, GE 707 polyesterimide, and Epon 825 epoxy. Processing problems, which resulted in the formation of voids when the solvent could not escape during curing, plagued both Pyre-ML and GE 707. The problems were insurmountable, and both materials were judged unsatisfactory.

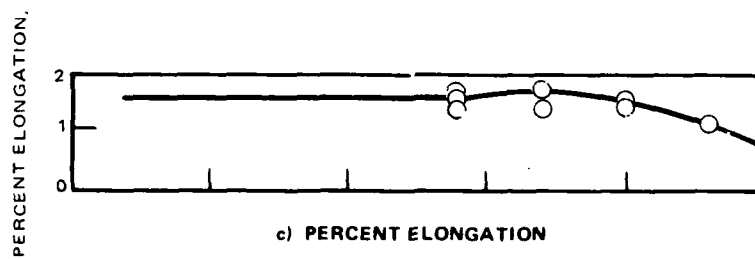
Epon 825 epoxy/HV hardener with both glass cloth and polyweb were examined. The insulation using the glass appeared to have a higher CIV. In addition, and more importantly, the thermal conductivity of epoxy/glass was substantially higher than the epoxy/polyweb.



a) TENSILE STRENGTH



b) MODULUS OF ELASTICITY



c) PERCENT ELONGATION

Figure 12. Effect of oil at elevated temperatures for 250 hours on epoxy/glass laminates.

Based on the results of the testing described above, the most attractive material for this application is Epon 825 with HV hardener and Volan A glass cloth. This insulation system has outstanding characteristics for this application, including:

1. High strength and toughness
2. Processing is not complicated
3. Low viscosity
4. Compatible with synthetic cooling oil
5. Excellent thermal conductivity
6. Good electrical properties
7. Low thermal expansion
8. High temperature durability.

Its principal limitation is low elongation, i. e., it is not very flexible. Whether it is flexible enough to meet the bending to install the pitch coils must be determined. The bending required can be reduced in two ways. First, the pitch coil can be rotated in the slot before it is bent. This happens because the encapsulated coils are narrower than the stator slots. Second, the pitch coil can be raised to the top of the slot to provide more clearance if needed.

IV. COIL FABRICATION EFFORT

INSULATION SYSTEM CONSTRUCTION

The coils are formed from ML insulated rectangular copper wire. The wire is 0.040 inch thick by 0.200 inch wide. There are six turns per coil wound edgewise, so that the coil cross section is 0.200 inch wide and $0.040 \times 6 = 240$ inches high.

To impregnate the coils, they are first wrapped with two layers of glass tape, 3-5 mils thick each. Each layer is butt wrapped, and the two layers are half lapped. The straight portions of the coil are enclosed by a metal mold. A wrapped coil placed in the mold is shown in Figure 13. A cross section of the mold partially closed is shown in Figure 14. When completely closed, the mold has no gaps and the coil dimensions will be constant over the length of the mold.

After closing the mold, the end turns are wrapped with shrink tape. The shrink tape is slit to provide ingress for the resin. Then the coil with the mold is placed in a box mold in a vacuum. The box mold is filled slowly with epoxy resin impregnating the coil. The resin system used is Epon 825 with Hughes HV hardener. After curing the box mold is removed, and the excess resin around the coil is broken off. Finally, the coil mold is removed from the straight portions of the coil and the shrink top stripped from the ends, leaving the encapsulated coil.

MOLD DESIGN

The initial design of the mold to encapsulate a coil was a very simple mold for straight segments. It consisted of a 5/8 by 5/8-inch angle and two

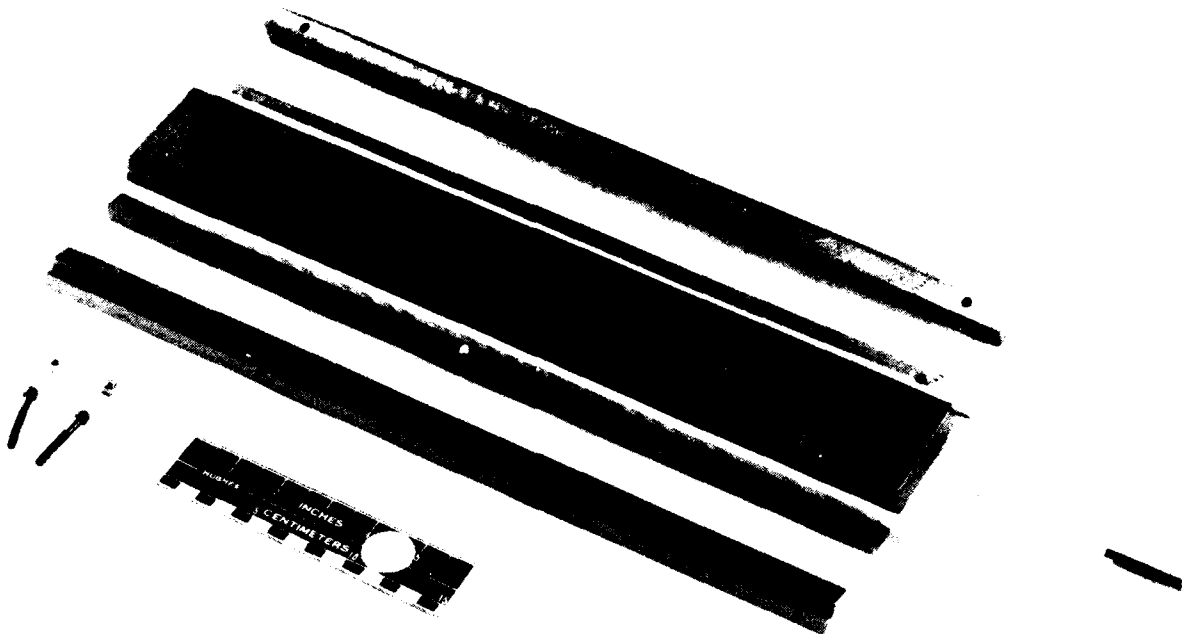


Figure 13. Coil mold and glass tape wrapped coil.

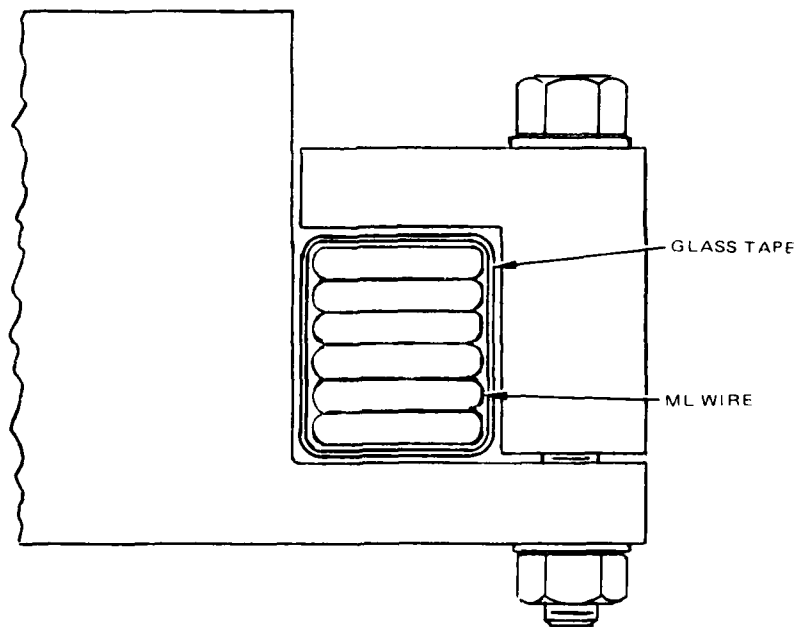


Figure 14. Cross section of coil mold.

straight bars bolted to each side, shown in Figure 15. This mold was used primarily to hold the six layers of ML wire during encapsulation.

The first coil mold (Figure 13) was a simple extension of the scheme used for straight segments. This mold was used first to make prototype coils. Five coils of slightly different construction were made. Subsequently, the mold was modified to reduce the insulation on each side. Small dimples were machined in the mold to make protuberances on the sides of the coil. The projections center the coil in the stator slot and make a uniform passage for the cooling oil. The design drawings of this mold are presented in Appendix E. The design drawings of the box mold used in conjunction with the above coil mold are shown in Appendix F.

The mold proved to be mostly satisfactory. The dimensions of the coils after encapsulation varied only a few mils, which was within the machining tolerance for the mold. The thickness of the epoxy was uniform around the coil because of the glass cloth that centers the coil in the mold. Finally, the coils could be removed easily from the mold. The only problem was flash at the corners of the coil. If the flash was more than about 5 mils thick, it was difficult to remove without damaging the insulation. It is evident that the design does not lend itself to closing perfectly at both corners. However, a method to repair damaged coils was developed and proved satisfactory during life testing. Later mold designs were changed to eliminate any flash.

The coil mold was redesigned to eliminate the flash problem and to increase the reliability of the coils. Attention was also directed to making the molds more suitable for production. First, the parting line was moved away from the corner to the side. The mold could now be closed tightly, eliminating any flash. The mold (Figure 16) now consisted of four identical half-cavities that were easy to machine and could be replaced individually. To minimize warping, the mold was made from 17-4 PH stainless steel. The design drawings are given in Appendix G.

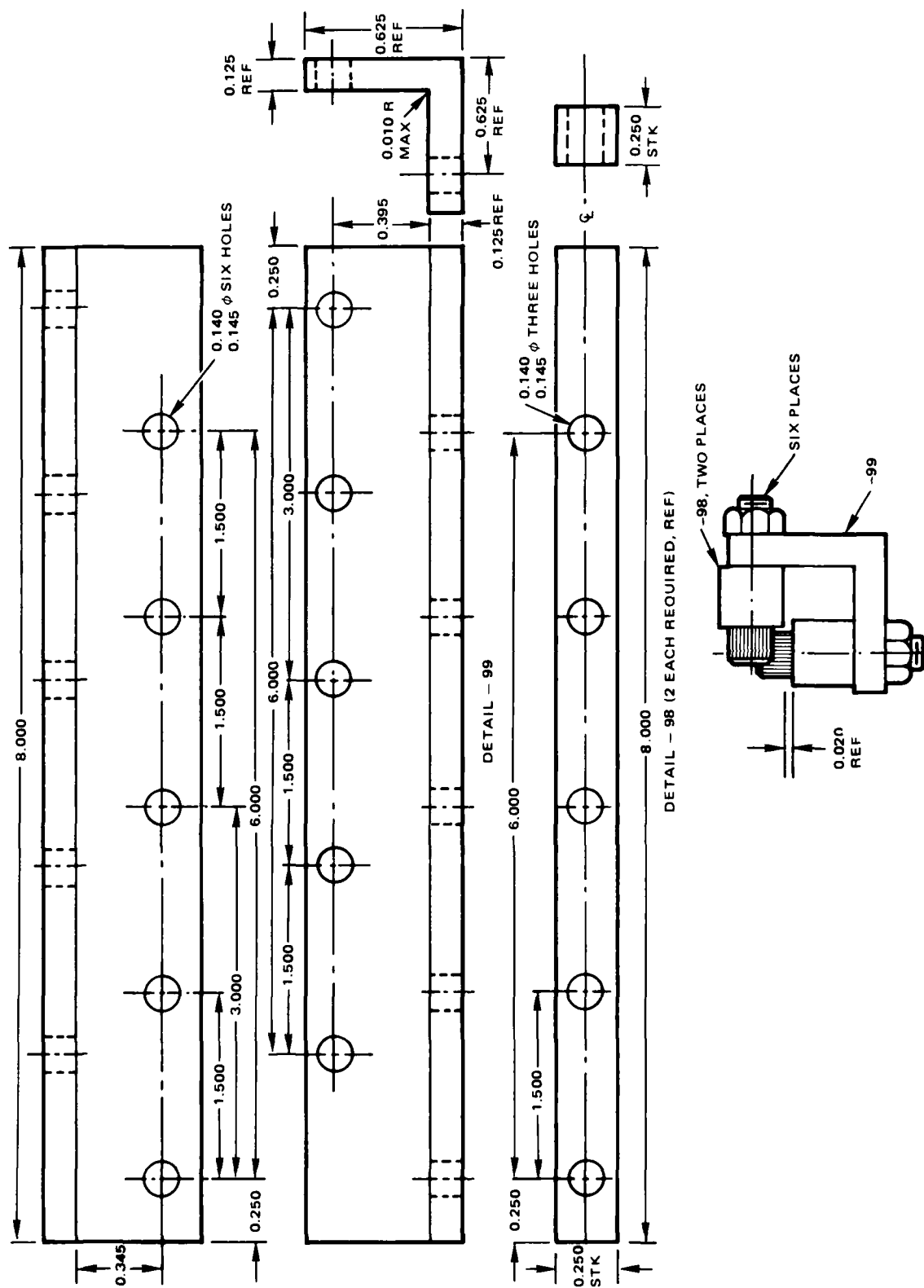


Figure 15. Mold for straight segments.

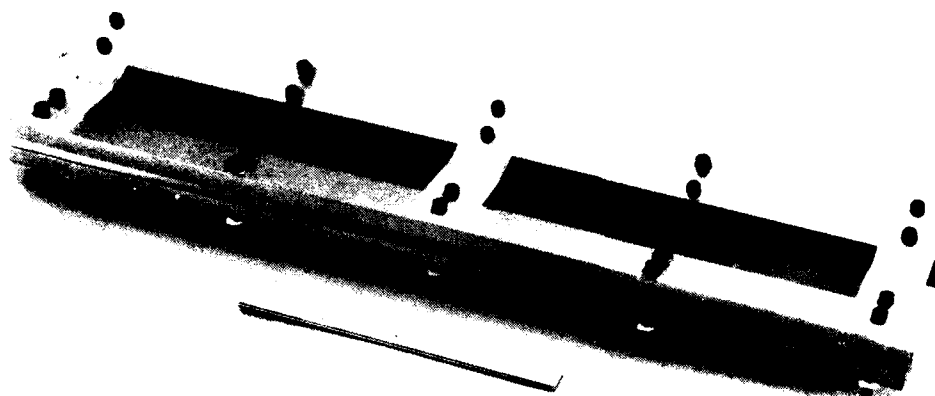


Figure 16. Redesigned coil mold and coil.

The box mold was also redesigned (Figure 17) to be easier to use and to be more suitable for production. The old mold had many joints that were difficult to seal. Only the cover of the new mold has to be sealed. The new mold was contoured to the coil mold, reducing the amount of resin needed. The design drawings are given in Appendix H.

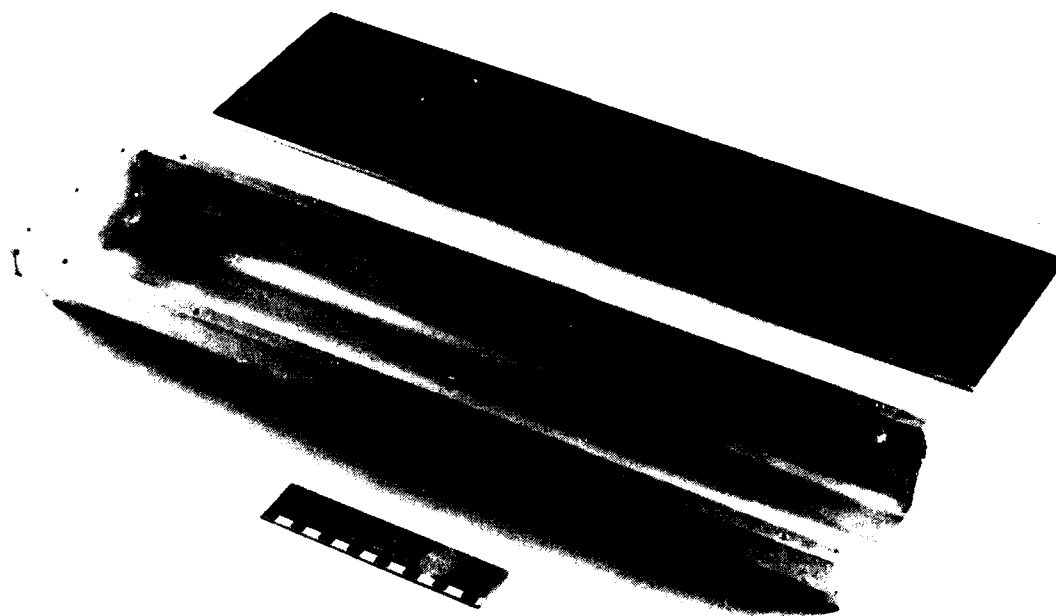


Figure 17. Redesigned box mold.

These molds were designed for straight coils. The use of straight coils greatly simplified the tooling. After successfully completing the

evaluation of the insulation system using straight coils, the next step was to design tooling taking into account the actual peculiarities of the generator and to fabricate coils in final form for test in an actual generator.

If the slots in the stator were straight, i. e. , parallel to the axis, straight coils would fit. Usual practice is to skew the slots to obtain a better waveform. In the Bendix generator, the slots are skewed one slot. The result is that the stator slot is a helix; therefore, the coil must have a helical shape.

The mold designed to make the helical or skewed coils is the same as the straight coil mold, shown in Figure 16, except the slot is a helix. The machining is more complex.

The straight slot was made in a vertical milling machine using an end mill. The mold was clamped to the table and moved past the end mill. The helical slot was made the same way, except the mold must be rotated as it moves past the milling cutter. The work is mounted on centers where one center is a dividing head that can be rotated. The process generates a helix. The pitch is determined by the angle of rotation for a given traverse of the table.

Drawings for the helical or skewed mold are given in Figure 18. The original concept was to have the mating surfaces of the molds cylindrical. However, planar surfaces that are simpler to machine were used. As a result, the depth of the slot varies ± 0.006 inch over the length of the mold, and the mold halves are no longer interchangeable. The upper mold half is rotated above center in the milling machine and the lower mold half below center. The tooling is complicated because of the large radius of more than 5 inches.

The skewed molds were machined with a Bosto-Matic numerically controlled four-axis machine, shown in Figure 19. The controls are in the cabinet at the right. The program tape and drive is behind the glass door. The machine is set up with the upper mold half. The dividing head is at the left of the table. A closeup of the finished upper mold half after machining is shown in Figure 20. Note, the mold is above the axis of rotation. The fixture for machining the lower mold half is shown in Figure 21. In this case, the mold is located below the centers.

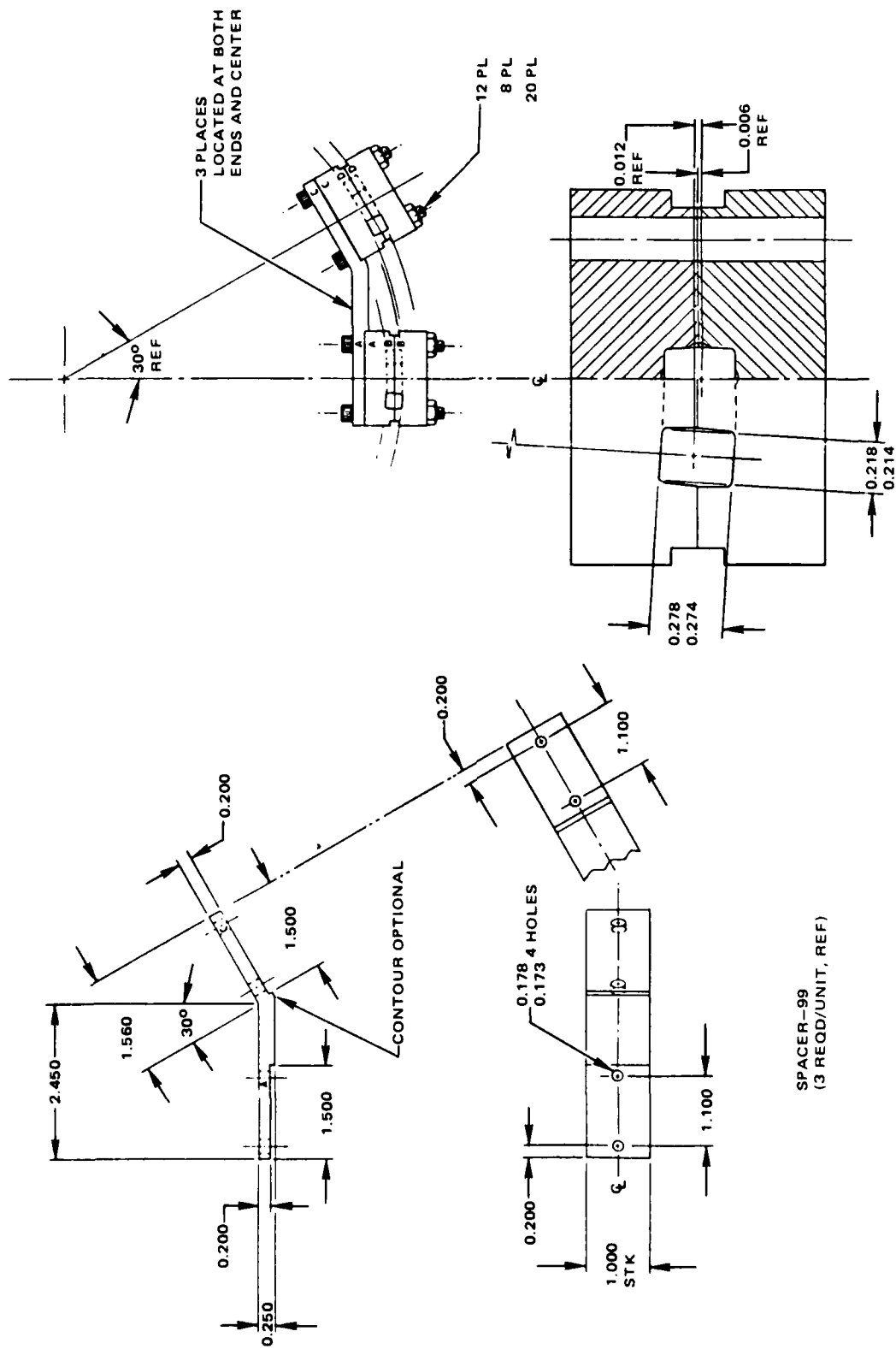


Figure 18. Skewed mold Dwg. No. 3707794 (Sheet 1 of 3).

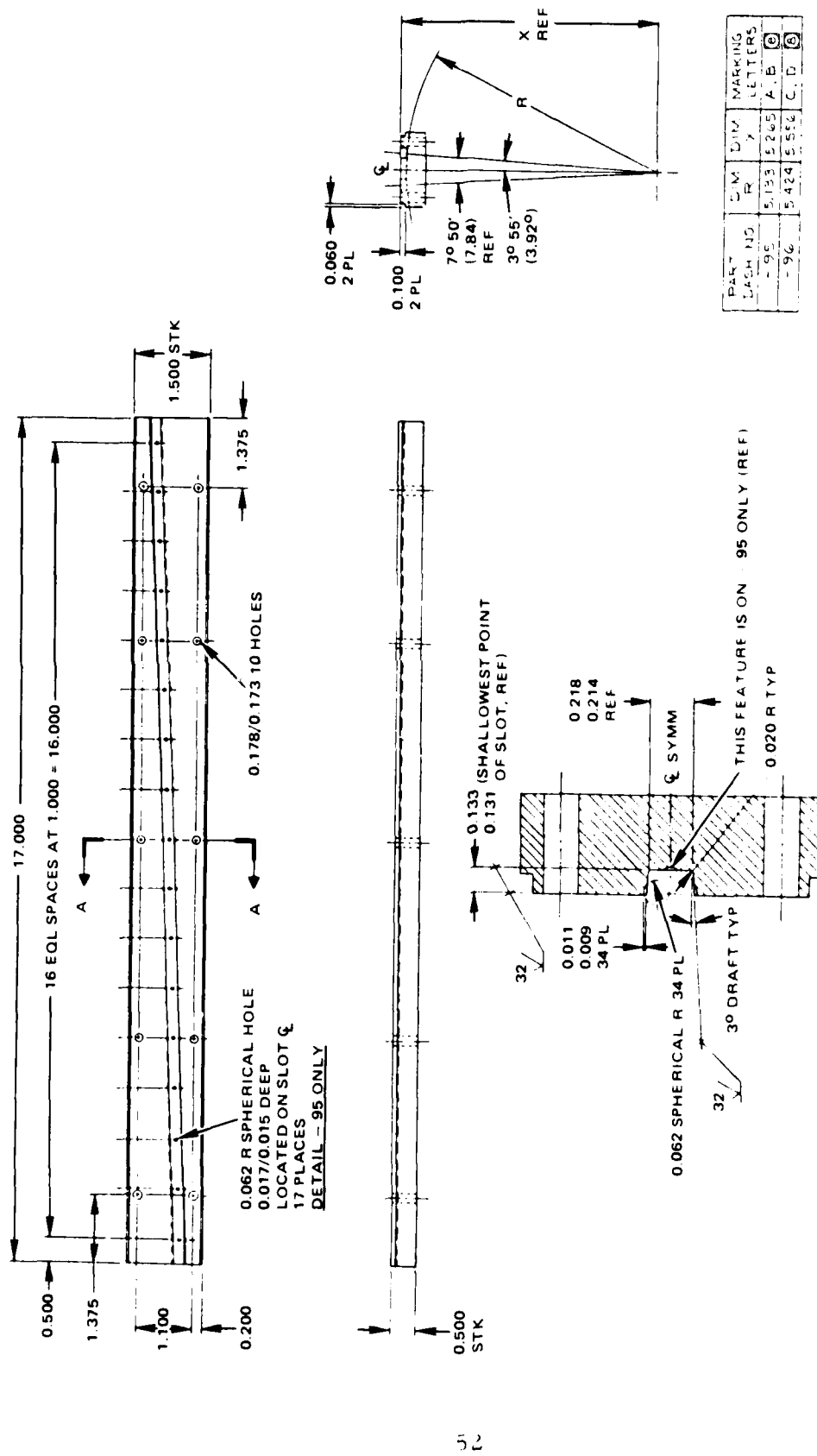
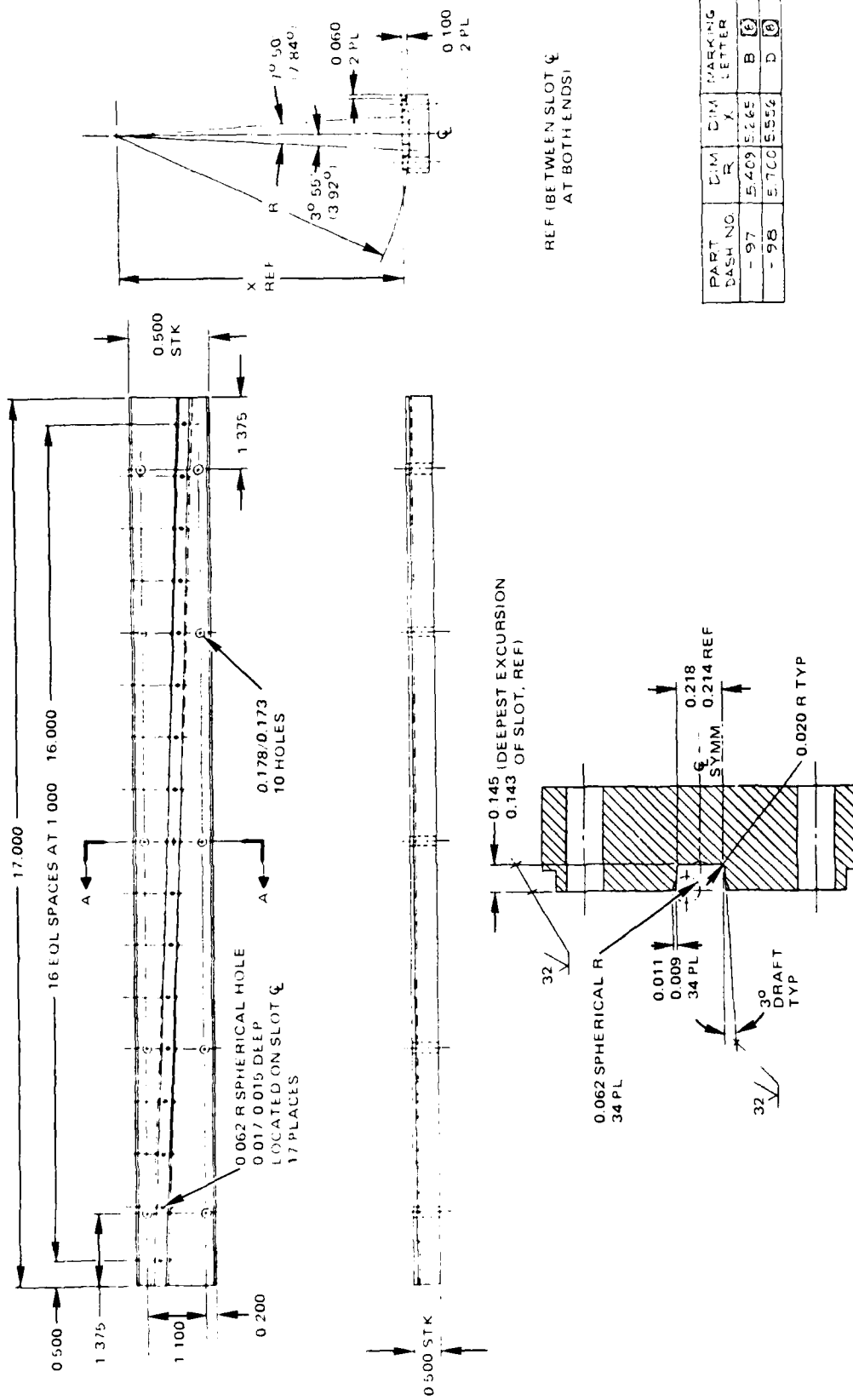


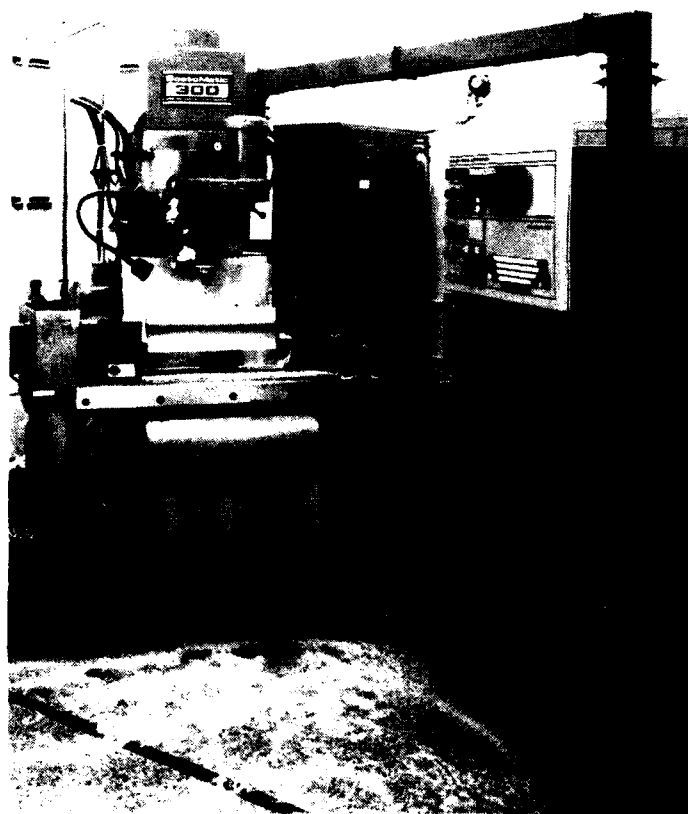
Figure 18. Skewed mold Dwg. No. 3707794 (Sheet 2 of 3).



PART DASH NO.	DIM R	DIM X	MARKING LETTER
- 97	5.409	5.265	B (F)
- 98	5.700	5.554	D (A)

SCALE 4/1
SECTION A A

Figure 18. Skewed mold Dwg. No. 3707794 (Sheet 3 of 3).



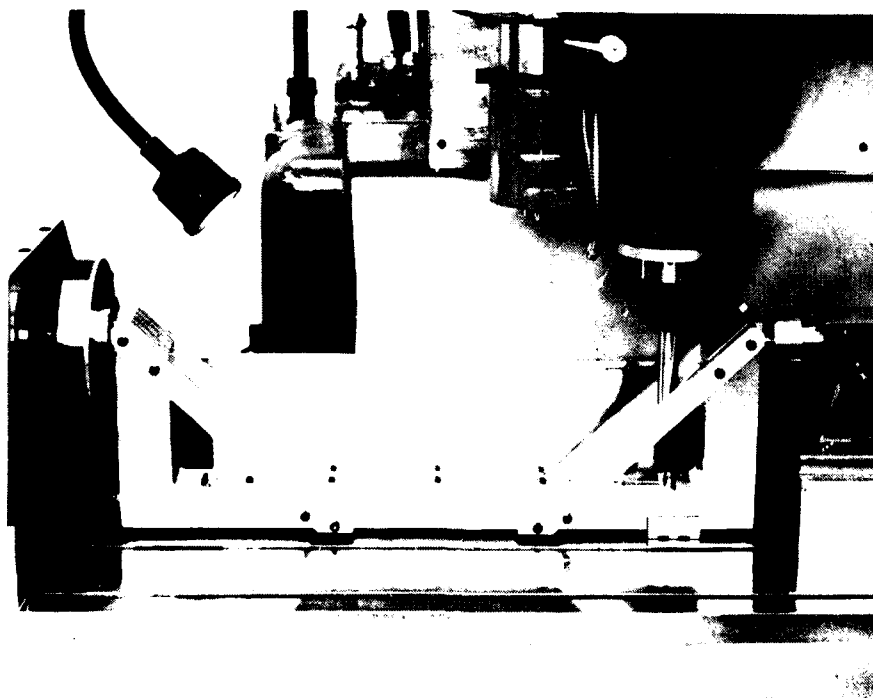
UCP 9-24-82-10

Figure 19. Bosto-Matic numerically controlled four-axis precision drilling machine (setup for upper mold half).



UCP 9-24-82-14

Figure 20. Closeup of upper mold half.



UCP 9-24-82-16

Figure 21. Fixture for lower mold half.

PROCESSING

The processing of the coils closely follows the Hughes processing specification, HP 33-5. The procedure used for impregnating the coils is summarized below:

1. Vapor degrease coil in Blakeslee degreaser.
2. Wrap coil with two layers of glass tape. Each layer is butt wrapped. The two layers are wound in opposite directions.
3. Apply a thin uniform film of Ram 225 mold release on all mold surfaces and bake in air oven.
4. Assemble coil mold.
5. Assemble wrapped coil in mold.
6. Wrap coil end turns with polyester shrink tape.
7. Heat tape with blow dryer and shrink until tight.
8. Carefully perforate tape every 0.25 inch all around to provide entry for the resin.
9. Assemble potting mold.
10. Seal all joints in the mold with Silicone 732.
11. Coat all screws and nuts with silicone grease. Cover with Silicone 732.
12. Assemble coil mold and coil in potting mold.
13. Arrange mold in vacuum vessel and pump down.
14. Weigh Epon 825 epoxy resin and HV hardener in the ratio of 100:18. Mix thoroughly.
15. Degas resin mixture at 10^{-1} Torr.
16. Introduce resin into bottom of potting mold and slowly fill to top of mold.
17. Continue pumping until vacuum reaches 100 microns.
18. Cycle to atmospheric pressure and pump down to 10^{-1} Torr.
19. Cure at 70°C and 90 psi for 12 hours.
20. Post cure in air oven at 120°C for 4 hours.
21. Disassemble potting mold.
22. Remove excess resin from around coil mold.
23. Carefully remove impregnated coil from coil mold.
24. Remove shrink tape.

REPAIR

The first coils made were plagued with minute nicks and cracks at the coil corners. The original mold for ease of manufacture had parting lines at opposite corners. The problem was caused by difficulty in removing the flash without damaging the coating. The repair procedures were developed as an expedient to continue the development work. The following procedure, which was developed, proved very successful. The early life tests were conducted with several repaired coils. The method follows the Hughes processing specification, HP 16-54, and consists of the following steps:

1. Clean area to be repaired with isopropyl alcohol and naphtha.
2. Heat coil in air oven to 70°C for 20 minutes.
3. Weigh Epon 825 epoxy resin and HVU hardener in the ratio of 100:25. Mix thoroughly.
4. Apply thin coating of resin mixture to affected area.
5. Degas at 10^{-1} Torr.
6. Cure in air oven at 70°C for 2 hours.

SUMMARY OF COIL DEVELOPMENT

Using the original coil mold, shown in Figure 16, five prototype coils were made. These coils were made primarily to evaluate the mold and develop the processing. The first coil had a layer of polyweb over a layer of glass tape. S/N 2, 3, and 4 had one layer of 7 mil glass tape only. The end turns of S/N 5 were impregnated with different epoxy in an early attempt to increase the flexibility. This step turned out to be unnecessary, and no further work was undertaken. The prototype coils were used for corona tests, bending tests, breakdown tests, turn-to-turn tests, and life test system checkout.

Then the mold was modified to reduce the amount of insulation and to add dimples to the mold for centering the coils in the stator slots. Eighteen test coils were made. The first nine coils had one layer of glass tape. Different methods were tried to reduce the thickness of the end turns to improve flexibility. Shrink tape proved to be satisfactory, although it

adheres to the epoxy and is somewhat hard to remove. Starting with S/N 13, the design was changed to two layers of 3-mil glass tape all over.

Shrink tape is used outside the mold for the end turns. No further changes were made in the construction of the coils during the remainder of the program except to improve the mold. The test coils were used for corona tests, bending tests, turn-to-turn tests, life test start-up, and life test.

Subsequently, a new mold was designed to eliminate cracks and nicks at the corners of the coil. A separate mold was made for each side of the coil with the parting line in the middle instead of at the corners, as shown in Figure 16. Sixteen coils were fabricated using the new mold. The coils were examined mechanically and visually, tested for pinholes using the conductive solution, and life tested.

Finally, to make coils for installation in a generator, a skewed or helical mold, shown in Figure 18, was made. Ten coils were fabricated which were tried in a stator to evaluate fit and installation requirements. The coils were installed satisfactorily. The fit appeared uniform over the length of the stator. The test was judged successful.

V. PROOF OF DESIGN TESTS

The Purchase Description, given in Appendix A, contains a requirement, Paragraph 3.10, that proof-of-design tests be performed. Usually these tests are a demonstration in actual operating environment that a component or system will meet performance and life specifications. In this instance, actual operating conditions can only be supplied by testing the stator coils in the generator, an option which is not available. Therefore, a set of tests is described in Paragraph 3.10 that duplicates as closely as possible the operating conditions. To carry out these objectives a Test Plan, Appendix C, was prepared in which the tests to be performed as proof-of-design of the stator insulation system are outlined.

Two different types of assemblies were tested to provide a complete verification. Stator coils identical in size and shape to those in the generator were used for most of the testing. Since some of the tests to be performed cannot be satisfactorily carried out on a complete stator coil, they were performed on segments of a stator coil.

The following tests were performed as proof-of-design of the stator insulation system:

1. Thermal conductivity
2. Temperature cycling
3. Dielectric breakdown
4. Bending
5. Conductive solution test
6. Life tests.

THERMAL CONDUCTIVITY

The maximum insulation temperature is quite sensitive to insulation thickness and thermal conductivity. If the designer chooses a material with a higher thermal conductivity, he has the freedom to use a thicker insulation to reduce electric stress or allow the material to have a lower temperature tolerance. Hence, the thermal transfer properties of the insulation system must be known accurately to balance the desire for maximum thickness for electrical strength and the temperature tolerance of the material.

Evaluation of the thermal conductivity of the insulation requires knowledge of the heat flow through the insulation and the surface temperatures of the copper and insulation. The heat flow can be determined from the power dissipated in the copper by electrical currents when the heat flow is uniform across a known area. The necessary surface temperature measurements can be obtained readily with thermocouples. Copper temperature can be measured effectively by using copper as a resistance thermometer which provides a bulk rather than a surface temperature. Any error is probably slight because of the high thermal conductivity of copper.

Experimental Procedure

A schematic diagram of the apparatus is shown in Figure 22. The test specimen was made from a piece of MI magnet wire, about 20 inches long, bent into a "U" shape. Potential leads were connected on each side, 5 inches from the center point. These were used to measure the temperature of the copper by measuring its resistance. After connecting the potential leads, the specimen was encapsulated with the insulation system. A typical test specimen is shown in Figure 23.

To minimize the temperature drop near the surface of the insulation, a liquid metal mixture of Cerrotru and Cerrolow was used for the bath. This mixture melts at 135°C , which was convenient for these measurements that were made at about 155°C . The bath was stirred to further improve the heat transfer at the surface. The temperature of the bath was measured by a copper-constantan thermocouple placed next to the specimen at the bottom of the "U".

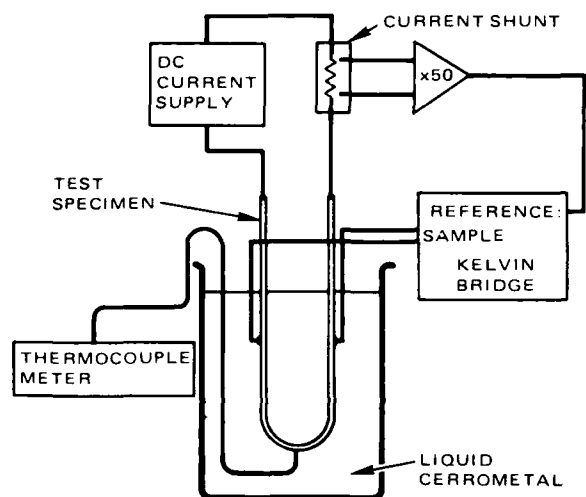


Figure 22. Apparatus for measuring thermal conductivity.

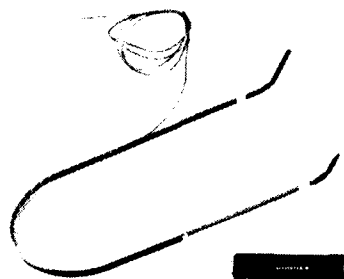


Figure 23. Thermal conductivity test specimen.

4R-56460

First, the temperature coefficient of the copper wire was measured by passing a small constant current through the specimen and measuring its resistance as the temperature of the bath was varied. A plot of the data is shown in Figure 24. The slope corresponds to a temperature coefficient $\alpha = 0.00397$ per $^{\circ}\text{C}$ that compares well with the published values of 0.00382 to 0.00393 per $^{\circ}\text{C}$.*

*The resistance of conductor at temperature, t $^{\circ}\text{C}$ is given by

$$R_t = R_{25} [1 + \alpha (t - 25)]$$

where R_{25} is the resistance at 25°C and α is the temperature coefficient. Differentiating

$$\alpha = \frac{1}{R_{25}} \frac{\Delta R_t}{\Delta t}$$

where $\Delta R_t / \Delta t$ is obtained from the slope of Figure 24.

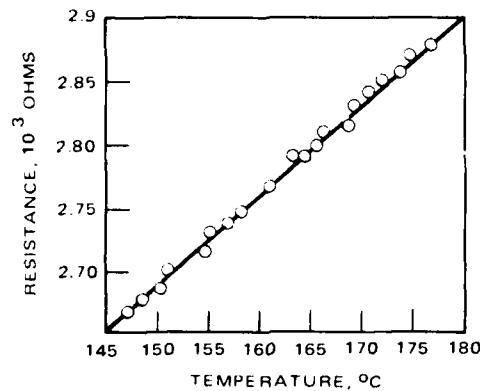


Figure 24. Resistance of copper wire versus temperature at constant current.

To measure thermal conductivity, the bath temperature was stabilized with a low current, 30 amperes, passing through the specimen. The bath temperature and the copper resistance were measured. Then the current was increased to 150 amperes. When the resistance of the copper stabilized (2 to 4 seconds), the resistance and bath temperature were measured. The measurements were repeated 9 to 12 times and averaged. The power dissipated in the specimen was calculated from the current and voltage. The temperature of the copper was determined from its resistance minus any change in the bath temperature. The power dissipated was calculated from the resistance and current. In a typical run, the power dissipated in the specimen was 1.2 watts at 30 amperes and 31 watts at 150 amperes. The heat conductance was calculated from the power dissipated and the temperature rise.

Results

Specimens made from ML magnet wire insulated with epoxy-polyweb, epoxy-glass cloth, epoxy-glass tape, and merely ML wire were measured. The thermal conductivity was calculated from Equation (2),

$$k = \frac{1}{G} \frac{t}{A} \times 22.8 \text{ Btu hr}^{-1} \text{ ft}^{-1} \text{ } ^\circ\text{F}^{-1} \quad (2)$$

where:

t = thickness in inches

L = specimen length = 10 inches

h = wire thickness = 0.040 inch

w = wire width = 0.200 inch

G = heat conductance in °C/watt

A = area in inches

The insulation area (including allowance for thickness) is

$$A = (2w + 2h + 2t) L \quad (3)$$

If the insulation thickness on the edges is different than on the sides,

$$k = \frac{1}{G} \times \frac{1}{\left(\frac{2w + 2t}{t_2} + \frac{2h + 2t_2}{t_1} \right) L} \times 22.8 \quad (4)$$

where:

t₁ = thickness on edges

t₂ = thickness on sides

The thermal conductivity, k, was calculated for each specimen. The results are presented in Table 9. All specimens were made from ML wire insulated with epoxy and glass or polyweb. In each case, the thermal conductivity of the epoxy-glass tape insulation system, including the ML, will provide adequate heat transfer across the insulation.

TEMPERATURE CYCLING

Three six-layer and five two-layer epoxy/glass samples were temperature cycled from 0 to 200°C for 30 cycles to determine resistance to temperature shock, thermomechanical stresses, and high temperatures. The test was conducted in air. Turn-to-turn CIV was used to ascertain failure. The data are presented in Table 14. The volts/mil are approximate since the dielectric thickness was calculated by measuring the sample thickness and subtracting the nominal wire thickness, 0.040 inch. It is apparent that the CIV did not change significantly as a result of the temperature cycling. It is concluded the epoxy/glass will probably be satisfactory thermally.

DIELECTRIC BREAKDOWN

Breakdown measurements were made on one straight segment and on nine coils. The straight segment was tested using the corona test apparatus as a dielectric breakdown tester. It has the advantage that the corona inception voltage can be determined in addition to the breakdown voltage. The measurement of the turn-to-turn breakdown voltage for a coil required design of special apparatus to induce 200 volts per turn at a reasonable current. The design of this apparatus is described next.

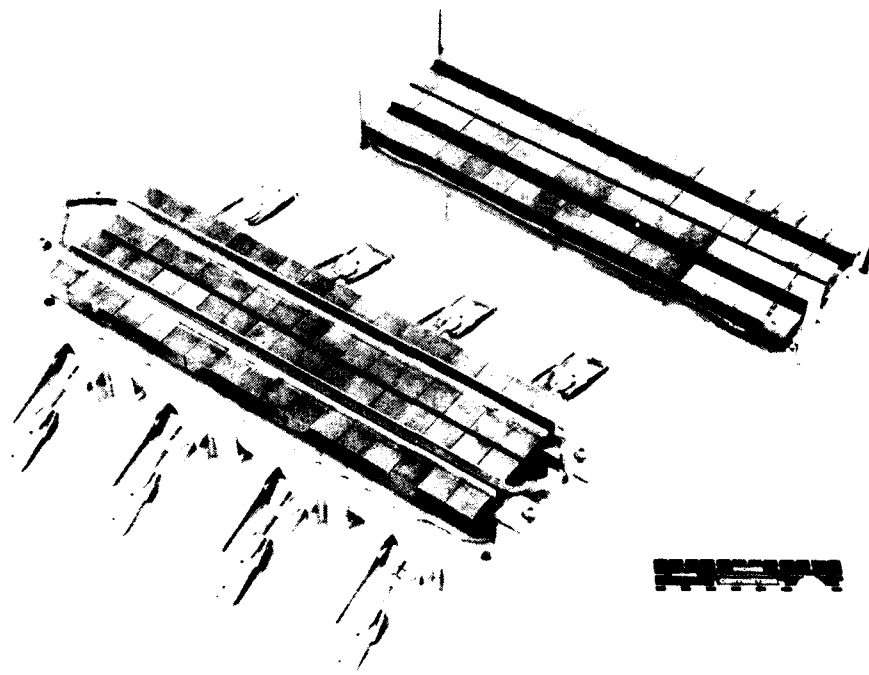
Design of Turn-to-Turn Test Apparatus

The objective was to induce 200 V per turn in a stator coil. Here 100 V, 1600 Hz were applied to a special transformer whose secondary was a stator coil. The test fixture is shown in Figure 25.

To maximize the coupling, a high μ material was desirable for the core. Hypersil (4 mil) was selected. Thirty-four standard cores with a cross-section of one square inch each were used. The cores were laid side by side with 17 cores on each side of the coil. A brass channel was inserted in the middle of the cores on each side to act as a primary winding and to locate the stator coil.

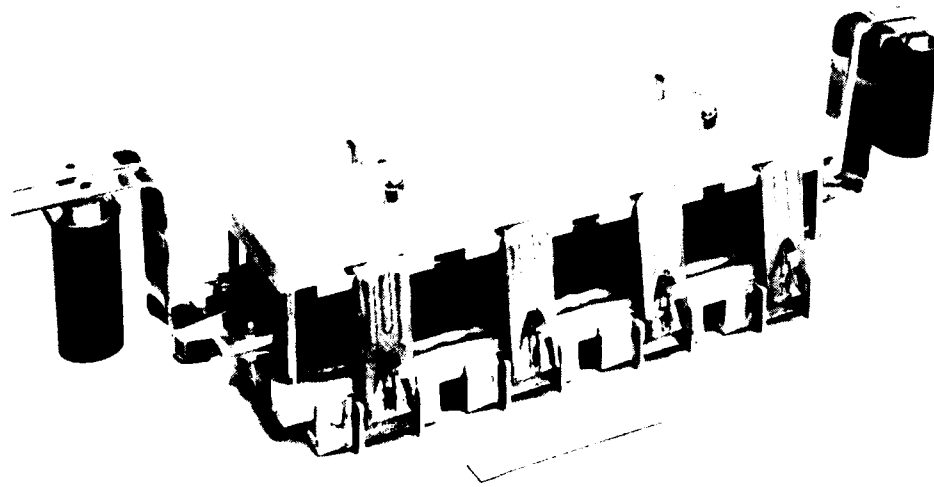
TABLE 14. EFFECT OF TEMPERATURE CYCLING
0 TO 200°C ON EPOXY/GLASS DIELECTRIC

Sample	Turns	CIV			
		kV		V/mil	
		Cycles			
		0	30	0	30
3	One to two	0.68	-	189	-
	Two to three	1.13	1.3	314	361
	Three to four	1.6	1.3	444	361
	Four to five	1.77	1.6	492	444
	Five to six	1.77	1.6	492	444
Average		1.42	1.38	436	403
4	One to two	0.70	0.96	194	267
	Two to three	0.57	0.63	158	175
	Three to four	1.15	1.08	319	300
	Four to five	0.78	0.93	217	258
	Five to six	1.1	0.94	306	261
Average		0.86	0.91	239	315
5	One to two				
	Two to three	1.1	1.32	306	367
	Three to four	0.7	1.25	194	347
	Four to five	1.5	1.75	417	486
	Five to six	0.6	0.91	167	253
Average		0.98	1.31	271	363
2	One to two	1.4	1.24	350	310
6	One to two	1.1	1.14	275	285
7	One to two	0.92	1.49	230	373
8	One to two	1.1	0.77	275	193
9	One to two	1.1	1.03	275	258
Average		1.12	1.13	281	284



4R-61884

a) TOP PORTION REMOVED



4R-57087

b) WITH TEST COIL SURROUNDED BY CORES
(NOTE CLAMPS HOLDING CORES TOGETHER)

Figure 25. Turn-to-turn test fixture.

The brass channels are interconnected underneath the fixture. The right end of each channel is connected to the left end of the other channel, with the input at the right ends. As a result, the same input voltage is applied to each primary. The configuration of the cores is the same as an "E" core; thus, the core area of the secondary is twice the area of the primary. The effective step-up ratio then is 6×2 or 1:12 for a stator coil of six turns. A schematic diagram of the circuit and calculation of the step-up ratio are given in Appendix I.

To reduce the primary current, 20 μF of capacitance was added in parallel to the primary to form a resonant circuit. Then the current was reduced from 18A to about 2A, as shown in Appendix I.

The actual inductance of the primary circuit depends critically on the air gap, which must be 1 or 2 mils. Because the stator coil must be replaceable (for testing different coils), standard core banding techniques were not suitable. A fixture was designed, shown in Appendix J, consisting of two fiberglass plates to which the core halves were bonded. To ensure the best alignment and smallest gap possible, an RTV adhesive was used to bond the cores. By maintaining a 0.1 inch thick bondline, a compliant mounting was achieved. A fixture plate was used for alignment. This flat aluminum plate had slots milled in the surface. The brass primaries were placed in the slots and the core bottoms stacked over the bars. After all cores were in position, 1/10 inch rubber strips were placed over them and generous quantities of RTV applied. Then the bottom fiberglass plate was pressed into the RTV and cured in place. The aluminum plate was removed and the process repeated with the mating core halves, being careful that each core was positioned over its proper mate. The side clamps on the plates were engaged lightly to ensure that all cores mated.

Results

The waveform for a good coil is shown in Figure 26a; the waveform for a coil after breakdown is shown in Figure 26b.

a) GOOD COIL



b) AFTER BREAKDOWN
(COIL TEMPERATURE = 100°C)

Figure 26. Waveforms ($V = 1 \text{ kV/cm}$, 1600 Hz).

Nine coils and one straight segment were tested for dielectric breakdown between turns. The parts were tested in air at $2000\text{V}/6 \text{ turns} = 333 \text{ V/turn}$.³ There were no failures. The results of the breakdown tests are summarized in Table 15. Prototype coil S/N 1 and test coils S/N 1 and 3 exceeded the turn-to-turn test requirement, but broke down to ground. This was attributed to the lack of the protuberances for centering the coils. One of the coils, Prototype S/N 1, and the six-layer segment were tested to breakdown to determine the limit of the insulation system. The data shown are for separate tests. The average breakdown was 7.9 kV, and the lowest was 6.8 kV.

BENDING TESTS

The coils are assembled in the stator in sequence as discussed in Assembly Into Stator. The coil arrangement at the beginning of the winding is shown in Figure 2. The first four coils are called pitch coils. Each must be bent up to install the last four coils. The amount of bending needed is shown schematically in Figure 27.

³Rated voltage is 73 V/turn. The required test voltage is 100 V/turn.

TABLE 15. SUMMARY OF BREAKDOWN TESTS

Coil		Turn-to-Turn 2000 VAC		Coil-to-Ground, kV
		Cold	Hot	
-	P1	O.K.	X	7.6, 7.9, 8.5
	P2	O.K.	O.K.	
	P3	O.K.	O.K.	
	P5			
	1	X		
	2	O.K.	O.K.	
	3	O.K.	X	
	4	O.K.	O.K.	
	5	O.K.		
Six-Layer Segment		5.6, 5.7 kV		6.8, 8.8
X = Broke down coil-to-ground				

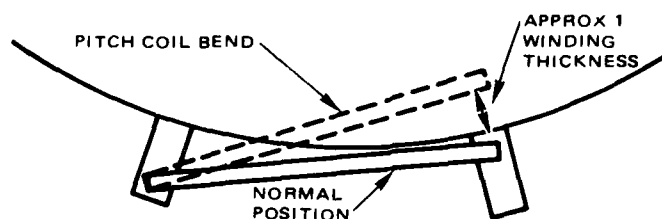


Figure 27. Bending of pitch coil during installation.

Four coils, prototype coil S/N 2 and test coils S/N 7, 9, and 13, were tested as follows to verify that the insulation was not damaged by bending and twisting during installation in the stator. The coils were tested one at a time. The coil to be tested was installed in the stator simulation fixture, shown in Figure 28, and subsequently bent so that another coil could be passed underneath the elevated side. The bending was repeated five times. To detect any damage, the coil-to-ground CIV was measured before and after bending.

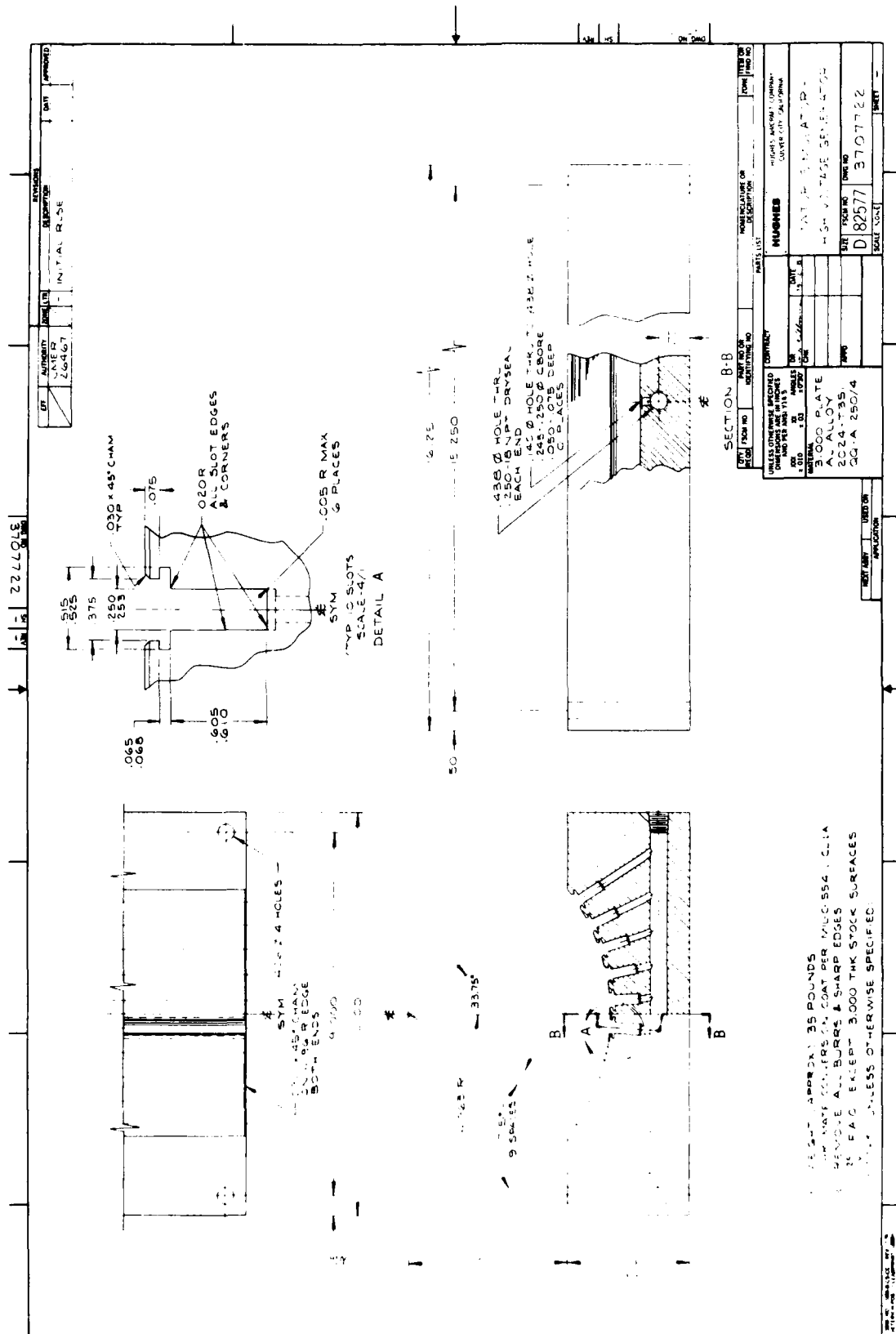


Figure 28. Full coil life test fixture.

For each coil the results of the tests indicated that there was no apparent change in CIV. In addition, no evidence of cracks or delamination of the insulation was found. Finally, the results indicate that the coils are flexible enough so that the pitch coils can be installed reliably.

CONDUCTIVE SOLUTION TEST

A test to detect cracks and pinholes in the coil insulation was developed to use as a screening test after encapsulation. The method consists of immersing the coil to be tested in a conductive solution of potassium sulfate. Also an electrode is immersed in the solution. A positive potential of about 150 VDC is applied to the electrode with the coil grounded. If the insulation of the coil has an aperture, current will flow through the conductive solution, i.e., from the coil to the electrode. The current could be detected with an ammeter, but the location of the fault would not be given. By adding phenolphthalein, the normally colorless solution will turn pink where there is current, giving a visual indication of any fault in the insulation.

A coil being tested that had a small pinhole is shown in Figure 29. The vessel is a large glass cylinder. Only the upper portion is shown. The location of the fault is indicated by the pink stream which can be seen emerging from the side of the coil.

The test has proven to be an efficient screen. Holes only a few mils in diameter can be located readily. It is nondestructive.

LIFE TESTS

Description of Generator

The specifications call out the generator stator to be 48 slot, two coils per slot. The line-to-neutral voltage is given as 3500 VRMS, making a line-to-line of 6000 VRMS as given. The current through each coil, which is the same as the per phase current, is 168 amps. This value is based on the cross sectional area of 0.200 inch by 0.040 inch rectangular conductor and a stator copper current density of 21,000 amps per square inch. Using the six-turn configuration and the dimensions called out, the resistance per coil is 0.021 ohm (at 20°C).



Figure 29. Coil test in conductive solution, coil S/N 9.

The line-to-neutral full load voltage of 3500 divided by 8 coils plus the IR drop results in 438 volts per coil, open circuit voltage. The volts per turn for six turns is 73 volts. The turn-to-turn potential specified is 100 VRMS. The turn-to-turn potential of 100 volts specified is assumed to include a design safety factor. Also the generator windings are assumed to be connected in a Y configuration with all neutrals available separately for testing purposes, suitably insulated from ground so that they can be connected

to the high voltage. Based on the full load current and the calculated resistance, the maximum power dissipated in each coil is calculated as 600 watts ignoring resistance increases with temperature rise.

Life Test Apparatus

The ideal test would be to install coils in an actual generator; however, this installation is not feasible or desirable at early stages of development. As a viable substitute, the life tests were conducted using a slotted test fixture machined of aluminum plate to provide slots for 10 coils. The design drawing of the test fixture is given in Figure 28.

The slots match the 16.25 inch length of those in the generator. Oil injection points are provided at the center of each slot. Epoxy/glass strips were fitted to the grooves at the top of the slots to channel the cooling oil. The test fixture was in an oil bath. The oil was circulated by a pump equipped with a heat exchanger, temperature control, and flowmeter. The bath was stirred to provide cooling of the end turns.

Current and voltage were supplied to the coils in the test fixture by an arrangement of power sources, as shown in Figure 30. Only complete coils were tested, either three or six at a time to balance the phases. A ganged three phase variac was used to adjust the high voltage. Individual variacs were used to adjust the current in each phase. The temperatures of the inlet oil, test fixture, and bath were monitored during the tests. Interlocks were provided for safety during unattended operation.

Startup of Life Test

The life test was started with six test coils, S/N 4, 5, 7, 8, 9 and 10. The remaining slots in the stator test fixture were filled with dummy coils. The oil was circulated hot for several hours to remove most of the air bubbles in the oil. Rated voltage was applied to the coils. After several hours of operation, one coil failed and within 30 hours a second coil failed. The

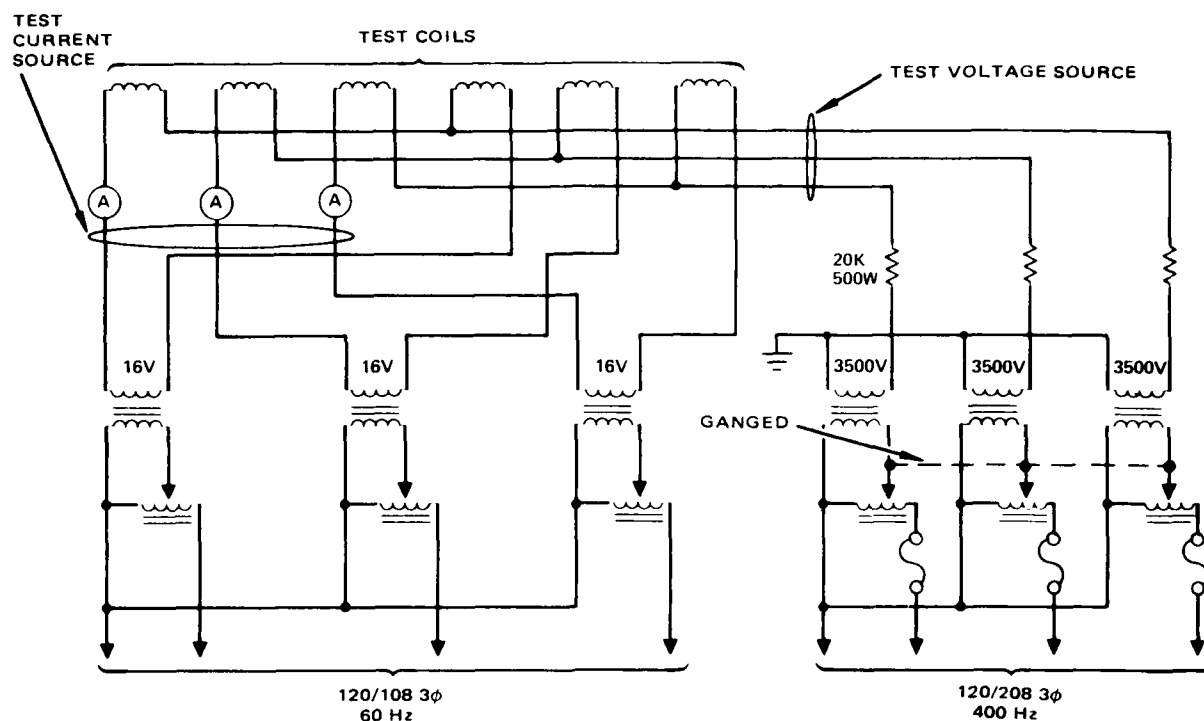


Figure 30. Life test schematic.

test was shut down when the third coil failed. Examination of the coils showed that S/N 7 failed at a corner. The breakdown was attributed to a large nick in the insulation that had been repaired with conformal coating.

Examination of the other coils showed a burned area on the side of the coil. In both cases the test at the end of the slot had been broken off, allowing the coil to press against the grounded fixture.

Before starting the test again, all the coils were checked for the absence of spacers. All missing spacers were repaired by attaching small pads of epoxy-glass laminate with epoxy resin. Eleven coils, S/N 4, 5, 10, 11, 12, 13, 14, 15, 16, 17 and 18, were installed in the test fixture for testing. The oil was heated to 100°C and 3 kV applied. The three empty slots were filled with straight coil segments that were unpowered.

The test was run for 52 hours when S/N 10 failed. S/N 17 failed at 109 hours, and the test was stopped. Examination of S/N 10 indicated that the breakdown was at a corner. This failure was caused by a large nick in the insulation that had been repaired. The failure of this coil and S/N 7 (discussed above) show that a thin conformal coating is insufficient to repair large flaws. The data are summarized in Table 16.

TABLE 16. SYSTEM CHECKOUT AND STARTUP

Test	Coils		Remarks	Operating Time, hours
	Started	Failed		
System Checkout	Proto 2, 3, 4	Proto 4	Coil unspaced in slot	30
Test Startup	4, 5, 7, 8, 9, 10	7, 8, 9	Failures caused by coils touching side of slot and large nick	
HV Test	4, 5, 10, 11, 12, 13, 14, 15, 16, 17, 18	10, 17	Pads added to center coils. Failure caused by large nick in insulation	109
Life Test Startup	11, 12, 14, 15, 16, 18	12, 15, 18	Failures caused by nicks	89

Six coils, S/N 11, 12, 14, 15, 16 and 18 were selected from the group that operated previously for 109 hours at 3000 volts. The coils were arranged sequentially according to phase. The remaining slots were filled with unpowered coils. The test was started at low power and gradually increased to 3000 volts and 138 amperes. After 94 hours, two of the soldered connections to the coils opened. Examination showed that the solder joints were inadequate. Also, evidence indicated overheating of the end turns. The connections were made larger to provide adequate current capacity. To measure coil temperatures, a thermocouple was inserted under the slot cover on top of S/N 16 to monitor the slot temperature. A second thermocouple was bonded on the outside of the end turns of S/N 14.

After the solder repaired, connections between the coils and the current transformers were repaired, the current to the coils was increased from 138 to 160 amperes at 3000 volts. At 3500 volts, after 16 hours one coil appeared to have failed, and the system was shut down to examine the coils. The failures were felt to be caused by nicks. The test data are given in Table 16. The coil temperatures measured during the above tests are given in Table 17a. The high temperature of the end turns was caused because the bath was not stirred. Stirring was added later.

TABLE 17. COIL TEMPERATURES FOR
100°C AMBIENT OIL

a. End turns cooled by normal convection of oil bath.

Volts	Amperes	°C		
		Oil	Slot	End Turns
3000	138	112		
3000	160	118	131	175
3250	160	120	134	176
3500	160	125	138	175

b. End turns cooled by stirring oil bath.

Volts	Amperes	°C		
		Oil	Slot	End Turns
1000	160	102	138	147
2600	160	107	127	131

First Life Test

The oil that had darkened and contained a large number of particles was filtered before the test. Six test coils were selected: S/N 6, 7, 9, 10, 13 and 17. Some of the coils were from previous tests. S/N 7 and 9 had failed during initial life test startup, S/N 10, 13 and 17 were used for test

with voltage only. S/N 10 failed after 52 hours; S/N 17 failed after 109 hours S/N 13 operated for 109 hours. All the coils were examined carefully for nicks and burned areas. These were repaired with Epon 825 epoxy and a modified hardener, HVU. A small amount of CAB-O-SIL silica flour was used to increase the viscosity to obtain sufficient buildup.

After repair, the coils were assembled in the test fixture and were connected electrically with two coils in series per phase. The phases were arranged sequentially. The empty slots were filled with dummy coils. The oil was circulated overnight to remove air bubbles. To heat the oil, the current was raised to 100 A. After 2 hours, the oil temperature was 90°C. The system was run for 24 hours with the coils at 110°C. Then rated power was applied; 3500 volts and 160 amperes. Two stirrers were used to cool the end turns. The oil bath was stabilized at 100°C. The coil temperature is shown in Table 17b. The next morning the voltage had decreased, and coil S/N 9 was removed. It was estimated the coil had failed in less than 6 hours. The test was continued with five coils. The test ran without incident for 190 hours. At that time, a line fuse had to be replaced. The failure probably was caused by operating close to the rated amperage. At 344 hours, the system shut down automatically. It was assumed that the power had been interrupted momentarily. The system was off overnight. The test was restarted in the morning and continued for 485 hours. At this time, the voltage was very low, and the test was stopped. Preliminary tests showed that the high voltage meter was not indicating properly and that two coils were shorted and the others possibly damaged.

The coils that had completed the life test were examined to determine the cause of failure. The coils were tested for high voltage breakdown. Three coils were shorted. One was the coil that had failed at the start of the life test. The coils were removed from the test fixture and examined visually for evidence of damage. S/N 9 that failed initially showed evidence of breakdown. In addition, three other coils showed signs of breakdown.

The results of the failure analysis are given in Table 18. From the data, it appears that S/N 6 failed which caused S/N 13 to overheat because of excessive current and it subsequently failed. Before the test was shut down, the remaining coils were damaged.

TABLE 18. FAILURE ANALYSIS OF LIFE TEST COILS

S/N	13	17	10	6	9	7
Phase	A ↓ Failed at 450 hours over-heated	B ↓ Over-heated	C ↓ Over-heated	A ↓ Failed at 450 hours	B ↓ Initial Failure	C Over-heated
Failure Analysis	Arc	OK	OK	Arc	Arc	Arc
Hi Pot	Short	1000 V	1000 V	1000 V	Short	Short

The results of the first life test are that five of six coils tested operated at full power for 250 hours as required and continued to operate up to 450 hours. The coils had been used previously and repaired. The repair procedure appears to be adequate and could be applied to all coils routinely. However, it is believed that the encapsulation processing can be further improved to eliminate flaws. Overall it was felt that the insulation system was most satisfactory.

Second Life Test

Before the second life test, the coil molds were redesigned (see Figures 16 and 17.) Also, a suitable acceptance test was developed. The objective of the life test was to verify the test plan and coil life time. It was planned to make enough coils to have two tests.

The first coils fabricated were tight in the new mold and were bent severely while being removed from the mold. The problem was corrected by machining a 3 degree taper on the sides of the mold. Coils S/N 2, 3 and 4

were installed in the life test fixture, and testing was started. Coils 2 and 4 had been bent severely during removal from the mold. The three coils were tested at full power. It was decided to run them until they failed, since two of the coils were judged to be damaged and not of the quality required for acceptance tests. After 107 hours the system shut down. Examination of the coils showed breakdown on the inside surface of S/N 3 that was caused by a crack that probably occurred while removing this coil from the mold.

Life test was continued with coils S/N 2, 4 and 5 installed in the test bed. Coils 2 and 4 were tested for 102 and 107 hours previously. After 35 hours, S/N 5 failed because of breakdown at the end turns. The failure analysis showed that the insulation had been cut while slitting the shrink tape before impregnation. The silicone rubber applied after the slitting had filled the cuts and hindered impregnation. This coil was repaired and the test continued. It failed again after 144 hours. Examination showed corona degradation at a repaired area. During repair, the resin did not flow into the hole. This coil was not retested since the problem was caused by faulty processing that had been corrected.

The life test was restarted with coils S/N 2, 4 and 7. (Coil 6 was judged to be a bad coil.) After 120 hours, the test was shutdown to add three more coils, S/N 8, 9 and 10.

After startup, the heat exchanger inadvertently was not activated and the oil temperature reached 176°C after 2 hours, at which time the system was shut down manually. Surprisingly, the coils visually did not appear to be damaged. Some evidence of heating was noted but no visible damage, and the test was restarted.

Since the life time of this insulation system appeared to be very long the test was extended to 1000 hours. Full power operating conditions were maintained, 3500 V, 168 amperes, ambient oil temperature 100°C , and stator temperature 117°C . The system was run essentially continuously, except it was shut down arbitrarily every 4 days to check oil condition, interlocks, electrical connections, etc.

After 897 hours, S/N 9 failed and was disconnected. The remainder of the coils continued to operate without incident. When all the coils had exceeded 1000 hours, the test was terminated. The test time was:

<u>Coil Number</u>	<u>Hours</u>
2	1447
4	1442
7	1161
8 and 10	1041

The oil was drained from the tank and the coils examined. Portions of the G-10 epoxy glass slot covers showed evidence of overheating. The amount of overheating varied. Some areas were badly discolored. Generally, there was only slight or no overheating. Large amounts of debris were found in all the slots.

The appearance of the coils overall was excellent. The coils were darkened according to temperature; the higher temperatures causing the most darkening. The end turns run the hottest and were quite black. Areas near the oil inlet orifice remained substantially unchanged. Also other portions were light. The general appearance of the surfaces was that they were in the same condition as when they were installed, except for darkening. Coil S/N 9 which failed at 897 hours was examined. No evidence of corona or arcing was found; however, a large nick was noted at one corner. This had been noted before installation. Also, one area was heavily covered with a black gummy deposit. Both of these areas appeared suspect and were investigated further. It appeared that the long-time failure mechanism is a gradual thermal degradation.

As part of failure analysis effort for S/N 9, a test in a conductive solution was performed. It was designed to visually reveal defects in insulation coatings. The test described in Conductive Solution Test consisted of immersing the coil in a solution of potassium sulfate, distilled water, and phenolphthalien. An electrode at +150 VDC was suspended in the solution

with the coil connected to ground. Current conduction at the site of a defect in the insulation causes the clear solution to turn pink marking the current path and thus visibly locating the failure. Coil S/N 9 displayed one pinhole failure located approximately in the middle of one leg of the coil, shown in Figure 29.

This test demonstrates the practicality of this method as a screen test for defective insulation. Employing this test as part of quality control screening for the coils is recommended.

Oil Evaluation

There was some concern that the MIL-L-7808 would adversely affect the insulation during the life testing. Initial measurements were made on three lots of oil. Samples 1 and 3 were unused. Sample 2 had been used in life tests and was measured initially after 500 hours of operation. The initial measurements are given in Table 19. The change in acid value and water versus time is given in Table 20. Acid value is equivalent to mg of KOH per mg of oil.

TABLE 19. COMPARISON OF MIL-L-7808 OIL SAMPLES

Sample Number	Acid Value	H ₂ O	Density
1	0.3	420.98	1.005515
2	0.5	905.93	1.03061
3	0.2	632.85	0.998345
Sample 1	Oil supplied by MERADCOM August 1975, Lot 20		
Sample 2	P. O. X4-419843-FT8 12-18-79 Used for startup and first life tests Operated at +100°C for 500 hours		
Sample 3	P. O. X4-451212-FLX 6-30-81 New unused oil		

TABLE 20. CHANGE IN OIL CONDITION WITH TIME
AT 100°C AMBIENT, SAMPLE 3

Parameter Measured	Hours of Operation		
	0	300	700
Acid Value	0.2	0.3	0.7
Water, ppm	633	539	159
Infrared Spectrum	No Change from Original		

The amount of water decreased, which might be expected. The acid value increased. Although organic acids are not particularly strong, it was felt the oil should not be used further for the life test. Therefore, the oil was changed in the second life test at about 900 hours. The oil was extremely dark. The coils were darkened in areas where the temperature was high. Otherwise, the coils looked the same as when they were installed in the test bed.

Third Life Test

The coils for the third life test were S/N 11, 12, 13, 14, 15 and 16. The conductive solution was used to test all the coils for pinholes. Surprisingly, several coils exhibited pinholes. The areas affected were at the outermost part of the end turns where the bend is very sharp. It is easy to scrape the insulation at this corner when removing the shrink tape. Also in these areas the insulation might be too thin. It is clear the test using the conductive solution is effective.

Operating conditions were full power with the inlet oil at about 100°C. Typical measurements of the operating parameters were:

Voltage	3500 V
Current	160, 156, 158 amps/phase
Oil Bath	97.5°C
Stator	105°C
Oil Flow	2.1 gpm
Oil Pressure	7 psi

It should be noted that the oil flow was higher than required.

To measure the coil temperature, a thermocouple was fastened, using epoxy, to the surface of the epoxy insulation at the end turns. A second thermocouple was wedged at the end of the slot between the coil and the slot cover. Typical coil temperatures for the above operating conditions were

Coil Slot	126.8°C
Coil End Turns	130.8°C

which gives about 170°C as the temperature of the copper. Since the above flow rate is higher than required, the pump was throttled to 1.1 gpm. However the oil foamed excessively and no measurements were obtained at this time.

The life test ran without incident and passed 500 hours successfully. It was planned to obtain sufficient data to estimate the MTBF for the insulation system. Therefore, the test was continued. At 833 hours, S/N 14 apparently failed and was disconnected. The cause of the failure was deferred until the system was shut down.

The test was continued with the five remaining coils and passed 2000 hours successfully. Subsequently, coil S/N 13 failed at 2172 hours and the life test was terminated at that time.

The failed coils (S/N 13 and 14) were removed and carefully examined. Both coils show evidence of corona on the side of the coil. The tracks were about 1 inch long and meandered along the length of the coil. It was apparent the failures did not occur quickly but took many hours to finally arc over and short.

The coils had turned dark. The amount of discoloration varied considerably. Some areas were black and very dark. Other places, especially near the cooling oil inlet, were unchanged and not darkened. The patterns of discoloration exhibited differences in detail, which suggested that the cooling of the coils was not uniform and was erratic. Possibly the coils were not centered perfectly, restricting the oil flow at those places. More dimples have been added to the new skewed mold as a precautionary measure. These should offset any variations in either the coils or the stator slots. At the time of the test, the most probable cause of non-uniform cooling was the large amount of debris in the oil that clogs the oil passages.

The oil flow at the top of the stator slot was also impaired. The slot covers were made from G10 epoxy glass board. At the operation temperature, the G10 softened and the dimples on the coils indented the G10, reducing the oil channel at the top of the coil. This test problem will not occur in the generator.

Overall, there was a general degradation where the epoxy appeared to have been eroded, baring the glass cloth. It was temperature and time related. The erosion was the greatest at the hottest parts of the coil. Where the coil was cool no wear was apparent. Coil S/N 13, which operated for 2172 hours, exhibited more damage than S/N 14 (the latter having run for only 800 hours). The degradation is probably a combination of thermal, chemical, and electrical effects that progress rather slowly.

Results

The first life test used coils that had repaired nicks and flaws. Nevertheless, five of the six coils operated at full power for 450 hours — nearly twice the number of hours required. It was felt that the performance was very satisfactory.

The second and third life tests were run with coils made with an improved mold. The quality of the coils was better, and flaws were largely eliminated. The tests verified the long lifetime of the insulation system. In addition, acceptance tests were applied to select the best coils.

The results of the second life test were that five coils operated for between 1000 and 1500 hours. One coil failed at 900 hours.

The results of the third life test were that five coils operated for more than 2000 hours. One coil failed at 800 hours.

VI. RESULTS AND CONCLUSIONS

An important aspect of this program was to select the dielectric to be used. Several candidates seemed to be suitable. Other materials were sought. The most promising were screened using test models. The combination of requirements severely limited the number of candidate materials. Most materials could not be processed without voids or were not compatible with the oil. An epoxy/glass system using Epon 825 with HV hardener was selected. Extensive testing demonstrated the suitability of the material. The CIV between turns was >4 kV. The breakdown voltage was 6 kV between turns and >15 kV to ground. Tensile specimens of epoxy/glass immersed in oil for 250 hours at temperatures up to 230°C indicated it should be safe to operate the insulation at temperatures up to 190°C . The percent elongation was only about 2 percent, i. e., it is not very flexible and may not bend enough to install the pitch coils. However, bending tests performed with coils subsequently, proved that the coils are flexible enough so that the pitch coils can be installed reliably.

A simple steel mold was used to encapsulate the first coils. The dimensions after encapsulation varied only a few mils, the thickness of the epoxy was uniform around the coil, and it was free of voids. The only problem was flash at the corners that was difficult to remove without damaging the insulation. A procedure to repair the coils was developed and was used for the initial life test coils. At the end of the life test, no repaired area had failed.

The mold was redesigned to have the parting line at the side. The mold could now be closed tightly, eliminating any flash. The coils made from this mold were used for the second and third life tests that operated for 1500 and 2200 hours.

AD-A130 376

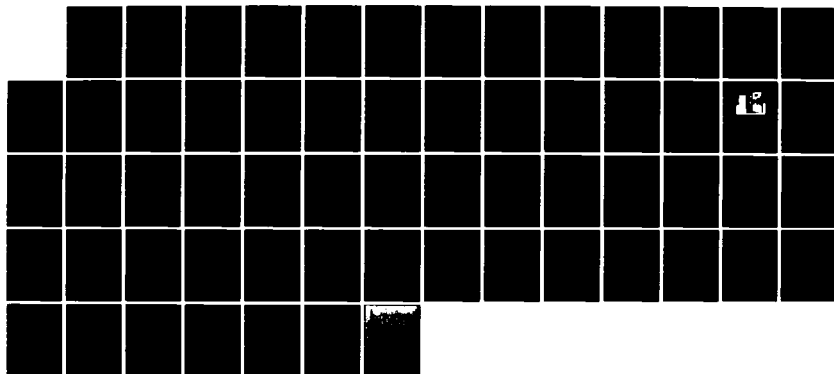
DEVELOPMENT OF A GENERATOR STATOR INSULATION SYSTEM(U)
HUGHES AIRCRAFT CO CULVER CITY CA TECHNOLOGY SUPPORT
DIV R S BURITZ APR 83 FR-83-76-686 DAAK78-79-C-0131

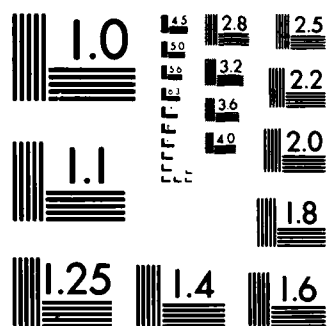
2/2

UNCLASSIFIED

F/G 10/2

NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

The maximum insulation temperature depends on the insulation thickness and thermal conductivity. High thermal conductivity will allow the use of thicker insulation to reduce electric stress, or a lower temperature can be maintained. The thermal conductivity of samples of ML wire insulated with epoxy was measured as part of the selection criteria. For ML wire alone the thermal conductivity, $k = 0.11 \text{ BTU hr}^{-1} \text{ ft}^{-1} \text{ }^{\circ}\text{F}^{-1}$, for ML wire and polyweb insulation, $k = 0.13$, for ML wire with glass insulation, $k = 0.19$. It is evident the epoxy-glass insulation will provide sufficient heat transfer.

Epoxy-glass samples and a coil were temperature cycled from 0 to 200°C for 30 cycles to determine resistance to temperature shock, thermo-mechanical stresses, and high temperature. There was no change in the CIV or evidence of any degradation of the insulation.

Dielectric breakdown measurements were made on a straight segment and nine coils. The measurement of turn-to-turn breakdown voltage for a coil required the design of a special apparatus to induce 200 volts per turn in a stator coil. Here 100 V, 1600 Hz were applied to a special transformer whose secondary was a stator coil. The coils were tested at 4.5 times rated voltage without failures.

Each slot in the stator contains two coils. The first four coils installed must be bent up to install the last coils that are in the bottom of the slot. Four coils were tested by bending five times each to verify that the insulation was not damaged by the bending and twisting required. To detect damage, CIV was measured before and after bending. The CIV did not change, and no visual evidence of cracks or delamination was noted.

A screening test was developed to detect cracks and pinholes. It consists of immersing the coil to be tested in a conductive solution containing phenolphthalein. A voltage is applied across the coil. A break in the insulation/results in an electric current that causes the solution to turn pink. The solution is only pink where there is current, otherwise it is clear. Thus, the location of the fault can be found easily. The test has proven to be an efficient screen. Holes only a few mils can be readily located. It is nondestructive.

The suitability of the insulation was determined by life testing under simulated full power conditions, with 100^o C ambient cooling oil. The initial test was run with six coils. One failed during the first few hours. The remaining five coils operated without incident for 485 hours. Although the first life test exceeded the 250 hours required, it was felt the encapsulation could be improved by redesigning the mold. The second and third life tests were conducted with coils made with the redesigned mold. The parting line on this mold was on the side, eliminating flash and attendant cracks and nicks. In addition, dimples were added to the mold that provide protuberances on the coil for centering it in the slot. The results of the second life test are given below:

<u>S/N</u>	<u>Hours</u>
2	1447
4	1442
7	1161
8	1041
9	897
10	1041

Coil S/N 9 failed at 897 hours. The remaining five coils operated until the test was terminated, when all the coils had operated for 1000 hours.

The results of the third life test are given below:

<u>S/N</u>	<u>Hours</u>
11	2172
12	2172
13	2172
14	833
15	2172
16	2172

Coil S/N 14 failed at 833 hours and S/N 13 failed at 2172 hours, at which time the test was terminated.

The coils had turned dark. The amount varied considerably. The patterns suggested that the cooling was not uniform. Possibly the coils were not centered well. More dimples were added to the skewed mold as a pre-

caution. However, the most probable cause was the large amount of debris present in the oil that clogs the oil passages. This problem could be corrected by filtering the oil.

Overall a general degradation occurred where the epoxy appeared to have been eroded, baring the glass cloth. The problem appears to be temperature and time related; the erosion is the greatest at the hottest portions of the coil. Where the coil was cool, no apparent damage was noted. Probably the degradation is a combination of thermal, chemical, and electrical effects that progress rather slowly.

The above molds were designed for straight coils to simplify the tooling. After successfully completing the evaluation life tests of the insulation system, the next step was to design tooling to fabricate coils skewed to fit the stator. A skewed mold similar to the straight mold was designed. Ten coils were fabricated that were assembled in a stator at Bendix* to evaluate fit and installation requirements. The coils, an exact fit, were installed easily. It should be pointed out that to achieve the correct shape, the coils (which are formed straight) must be bent to fit the mold before encapsulation.

Finally, it is concluded that a successful insulation system has been developed and amply demonstrated. The insulation has excellent oil compatibility and superior thermal conductance. The coils operated satisfactorily at full power and at actual service temperatures. The coil life time is greater than 500 hours and probably more than 1000 hours.

*Electric Power Division, Eatontown, New Jersey

APPENDIX A
PURCHASE DESCRIPTION FOR
DEVELOPMENT OF A GENERATOR STATOR
INSULATION SYSTEM

APPENDIX A
PURCHASE DESCRIPTION FOR
DEVELOPMENT OF A GENERATOR STATOR
INSULATION SYSTEM

2 October 1978

1. SCOPE

1.1 SCOPE

This Purchase Description covers development of a stator insulation system for a light weight, multi-phase, high voltage, high capacity, intermittent duty, short life electrical alternator. The insulation system is to be applicable to a class of generators having characteristics generally similar to those for which characteristics are specified herein as being typical, but not necessarily specific.

1.2 CLASSIFICATION

Because of the unique requirements of the alternators involved, the generally accepted industry classification system for electrical insulation systems, based on long life at specific temperature rises, need not apply.

2. APPLICABLE DOCUMENTS

2.1

The following documents of the issue in effect on date of invitation for bids or request for proposal form a part of this Purchase Description to the extent specified herein:

SPECIFICATION - MILITARY

MIL-L-7808 Lubricating Oil, Aircraft Turbine Engine, Synthetic Base

MIL-L-23699 Lubricating Oil, Aircraft Turbine Engine, Synthetic Base

3. REQUIREMENTS

3.1 DESCRIPTION

The contractor shall design, test, and evaluate (through commonly accepted statistical methods) a stator insulation system to meet the requirements specified herein. The insulation system shall be compatible with a cooling concept wherein a coolant is injected into the stator slot at approximately its midpoint and flows along the slot between the coil and the stator slot surface, to be discharged at both ends of the slot. Space between the slot and the coil are utilized to provide coolant flow passages. The end turns are cooled by directing a spray of the same coolant against them. The stator coils are to be of the preformed type and stator slots are to be of the open, straight-sided configuration. Design of the insulation system shall be such that completely insulated coils can be inserted into the slots and wedged into place without necessity for impregnation or any other supplementary insulation process after coils are in place in the stator.

3.2 OPERATING PARAMETERS

The insulation system shall be designed for the following operating conditions of the stator.

- a. Potential to ground - 3500 volts rms
- b. Phase-to-phase potential - 6000 volts rms
- c. Turn-to-turn potential - 100 volts rms
- d. Stator copper current density - 21,000 amps/in²
- e. Output frequency - 1000 Hz

3.3 DUTY

The generator will be required to operate for intervals of 120 seconds (with a duty factor of 50%) at full load. Full load will correspond to those conditions listed in 3.2.

3.4 LIFE

The insulation system shall be suitable to allow the alternator to provide full load for a period of not less than 50 hours. This requirement corresponds to at least 3000 operating intervals as described in 3.3.

3.5 COILS

As part of the work to be performed the contractor shall prepare and test coils utilizing the proposed insulation system. If the contractor so desires, the Government will supply uninsulated coils in sufficient number for preparation of finished coils by him. Each of these coils shall consists of six turns of 0.200 inch by 0.040 inch rectangular copper wire insulated with heavy ML coating. Coil span is 2.85 inches, overall coil length is approximately 17 3/4 inches and the straight (slot) part of the coil is approximately 17 3/4 inches. Coils shall be insulated over the entire length of turn to withstand the voltages given in 3.2.

3.6 SLOTS

The coils shall be mounted and tested in a slotted fixture to simulate as closely as economically practicable an actual generator stator stack with the following dimensions: ID=10.1 in. OD=13.3 in., Length=16.25 in. and the number of slots is 48. Slots shall be 0.250 inches wide and have a depth of 0.66 inches. The active depth of the slot accommodating the winding is 0.604 inches and 0.056 inch is used for the wedge securing the winding in the slot. Each slot shall accomodate two coil sides, coils being shaped such that each has one side at the bottom of a given slot and the other side at the top of another slot. The fixture shall accept at least twelve coils. Testing shall be accomplished with approximately 0.15 gal/min of cooling fluid flowing through each slot.

3.7 COOLANT

The insulation system shall be compatible, chemically and in all other respects, with all of the following cooling fluids: MIL-7808 lubricating oil, MIL-L-23699 lubricating oil, and silicone electrical insulating fluids of suitable viscosity.

3.8 AMBIENT TEMPERTURE

The insulation system shall be designed for machines which will operate in all ambient temperatures between -50°F and 125°F.

3.9 DESIGN APPROVAL

Prior to fabrication and test of coils the contractor shall present details of the proposed insulation system(s) to the Government for approval. Upon written acceptance of the proposed design(s), the contractor shall proceed with the work. Any change in design will require similar approval.

3.10 PROOF OF DESIGN

Test and evaluation shall be accomplished in the fixture described in 3.6 with a multi-phase power supply. The contractor, prior to the test, shall prepare a test plan for approval by the Government outlining how he proposes to demonstrate compliance with the requirements of 3.2, 3.4, and 3.8. Upon written approval of this plan by the Government, he shall proceed with the work. Any change in the test plan will require similar approval. Test of the insulation system shall include, but not be limited to tests for corona onset and corona extinction voltages, insulation life test, and insulation break-down voltages (coil-to-ground, coil-to-coil and turn-to-turn). Tests shall be performed with flow of cooling fluids in the slots at approximately 100°C and at the rate specified herein. The life tests shall be performed with a group of coils connected in 3 phase such that end turns of the coils are exposed to line to line voltages. The frequency of the power supply used shall be at least 400 Hz and the test shall be run for not less than 250 hours at rated voltage. The exact time is subject to agreement between the Government and the Contractor for the most reasonable definition of success. In addition to high voltage tests the following two tests shall be performed by the contractor: Heat conductivity for the insulation system shall be determined by test. This data shall be interpreted to provide an estimate of maximum copper temperature and temperature drop across insulation using the duty specified in 3.3 and oil flow specified in 3.6. Since coils will be slightly bent and twisted during installation in the stator slots, a mechanical test shall be devised and performed to ensure that the insulation is not damaged during such operation.

APPENDIX B
SUMMARY OF CONTRACT MODIFICATIONS

APPENDIX B
CONTRACT MODIFICATIONS

MOD	DESCRIPTION
P00001	Date change
P00002	<p>Section F, Add the following new paragraph:</p> <p style="padding-left: 40px;">'F.5 CLIN 00004, Magnet Wire Evaluation. The work required by this CLIN 0004 shall include the following:</p> <p>a. Problem Definition:</p> <ul style="list-style-type: none">(1) Perform tests to evaluate effects of the wire flaws on performance.(2) Fabricate specimens with and without defects and test for corona.(3) Determine the closest "easy to fabricate" manufactures' standard wire sizes. <p>b. Improved Wire Manufacturing Techniques:</p> <ul style="list-style-type: none">(1) Review technical problems with wire manufacturers and determine those capable and willing to improve the wire.(2) Screen wire manufacturers and reproprocessors.(3) Survey acceptable wire manufacturing candidates.(4) Evaluate samples of improved wire.

c. Specification Sheet:

- (1) Develop and provide a wire procurement specification sheet to augment current specifications.
- (2) Devise an inspection procedure which can be used for selection of wire with the quality required for the intended use.

P00003 Date change

P00004 Modify paragraph 3.10 to expand life testing to include operation at full power. Modify oil circulating system for a heat exchanger. Test and debug system. Run the life tests for 250 hours. Conduct failure analyses.

P00005 Add the following new paragraph to include additional contract line item:

 "0005 Primary redesign effort of mold

 0005AA Design and Fabricate Gauge

 0005AB Fabricate 15/20 coils

 0005AC Develop suitable acceptable test plan and conduct life test

 0005AD Investigate conducting solutions"

P00006 Add the following new paragraph to include additional contract line item:

 "0006 Identify another candidate system, making use of new materials (developed under CLIN 0005). Desired characteristics are improved temperature capabilities, dielectric strength and flexibility.

 0006AA Fabricate twelve (12) coils using new candidate system.

0006AB Apply approved acceptance testing
developed under CLIN 0005.

0006AC After screening the twelve (12) coils,
conduct life tests at a minimum of 3500
volts, 400 Hz, 160 amps per coil, with
approximately 100°C rated oil flow. Coils
shall be tested individually until a minimum
of 250 hours are achieved.

- P00007 1. CLIN 0006 is to be deleted in its entirety and shall now read:
"CLIN 0006 - Design and Fabricate a new impregnation
mold which implements the stator slot skew of 1 slot
pitch."
2. CLIN 0006AA - is to be deleted in its entirety and shall
now read:
"CLIN 0006AA - Fabricate ten (10) coils using the new
impregnation mold."
3. CLIN 0006AB - remains unchanged.
4. CLIN 0006AC - Delete in its entirety.

APPENDIX C
TEST PLAN

UNCLASSIFIED

REPORT NO. FR80-76-703
HAC REF. NO. E5112

CONTRACT NO. DAAK 70-79-C-0131

STATOR COIL INSULATION SYSTEM TEST PLAN

MARCH 1980

AEROSPACE GROUPS

HUGHES

HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

UNCLASSIFIED

C-1

TEST PLAN
PROOF OF DESIGN TEST

for

Development of a Generator Station Insulation System

Contract DAAK70-79-C-0131

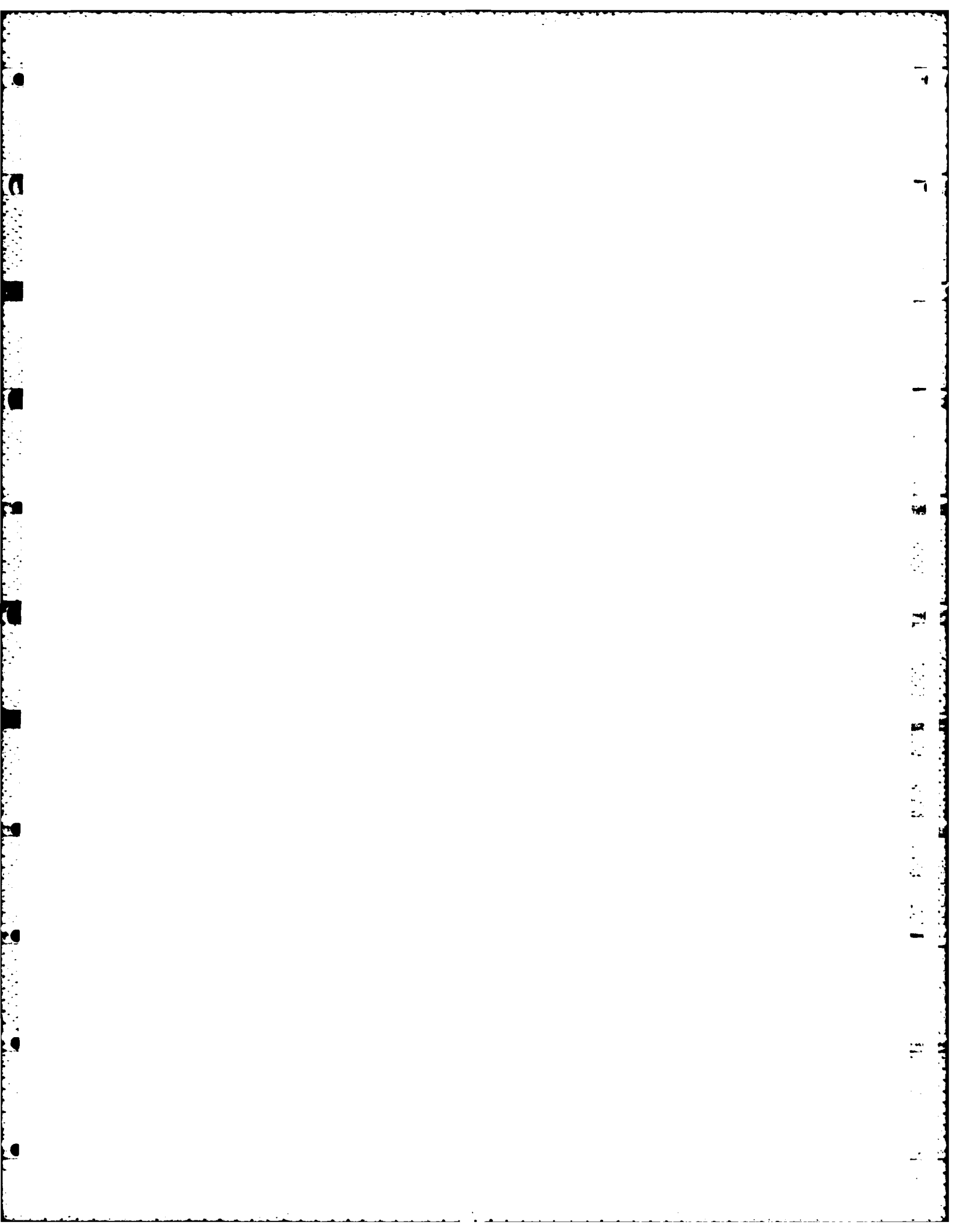
March 1980

Prepared for:

U. S. Army Mobility Research and Development Command
Fort Belvoir, Virginia 22060

by:

Developmental Products Laboratory
Technology Support Division
Electro-Optical and Data Systems Group
Hughes Aircraft Company
Culver City, California 90230



CONTENTS

1.0	INTRODUCTION	1-1
2.0	PURPOSE AND OBJECTIVES	2-1
3.0	ASSEMBLIES TO BE TESTED	3-1
3.1	Complete Stator Coil	3-1
3.2	Stator Coil Sections	3-1
4.0	TESTS AND TEST SET-UPS	4-1
4.1	Corona Testing	4-1
4.2	Life Test	4-6
4.3	Bending Test	4-7
4.4	Temperature Cycling	4-9
4.5	Dielectric Breakdown	4-10
5.0	OVERALL TEST PLAN	5-1
5.1	Arrangement of Tests	5-1
5.2	Number of Specimens	5-1
6.0	UNUSUAL TESTS	6-1
7.0	SCHEDULE	7-1

1.0 INTRODUCTION

This document contains the Test Plan required for Contract DAAK70-79-C-0131 by Exhibit A of the Contract, DD form 1423, sequence number A003. This report conforms to the requirements of DD1423, and in addition to the requirements contained in paragraph 3.10 of the Purchase Description, the DD form 1664 referenced by DD1423, and amendments thereto.

THE UNIVERSITY OF CHICAGO PRESS
1207 EAST 58TH STREET
CHICAGO, ILL. 60637
U.S.A.
LONDON
WINDMILL PLEASANT
HANTS

2.0 PURPOSE AND OBJECTIVES

Paragraph 3.10 of the purchase description contains a requirement that a Proof of Design test or tests be performed. A Proof of Design test is normally understood to be a demonstration in actual operating environment that a component or system will meet performance and life specifications. However, in this instance actual operating conditions can only be supplied by testing the stator coils in the generator for which they are intended, an option which is not available. Therefore, a set of tests is described in paragraph 3.10 which duplicate as closely as possible the operating conditions. To these, other tests have been added by the Contractor, who believes that they will further assist in the Proof of Design. Because of the limitation noted above, not all elements of the operating environment can be produced simultaneously. Since the failure mechanisms have been previously identified by the Contractor, and are separable, it is believed that the testing to be described will adequately prove the design.

3.0 ASSEMBLIES TO BE TESTED

Two different types of assemblies will be tested to provide a complete Proof of Design, because of the limitation discussed in 2.0, above.

3.1 COMPLETE STATOR COIL

Stator coils identical in size and shape to the presently (unsuccessfully) used coils will be used in the majority of the testing. These coils will be insulated using the systems developed as per paragraph 3.0 of the purchase description, which system will also have been approved per paragraph 3.9 of the purchase description. It is anticipated that these coils will be, in their finished form, sufficiently like the presently used coils that they could be installed in the stator of Bendix Brushless Generator 28B371-1.

3.2 STATOR COIL SECTIONS

Certain of the tests to be performed, for example the turn-to-turn corona tests, cannot be satisfactorily performed on a complete stator coil. These tests will be performed on segments of a stator coil, so that individual coil turns may be isolated. A segment is the normal straight part of a stator coil, appropriately terminated at either end to simulate actual use.

4.0 TESTS AND TEST SET-UPS

The following tests will be performed as proof-of-design of the stator insulation system:

- Corona tests
- Life test
- Bending test
- Temperature cycling
- Breakdown.

The requirement for the measurement of the thermal conductivity of the insulation system is presently being met in a program phase prior to proof-of-design.

In the sections that follow, each test is described, the actual test set-ups are described, the required equipment is identified, test procedures and parameters are given, data sheets are shown, and acceptance criteria given.

4.1 CORONA TESTING

Corona tests of the insulation will be conducted to demonstrate that the insulation does not have voids or other discontinuities which could result in early failure through corona damage.

4.1.1 Corona Test Set-Up

Two types of specimens will be used in the testing: complete stator coils, and coil segments. All tests on the complete coils will be conducted in the stator simulation fixture, Figure 1. Tests on the stator segments will be conducted both in the fixture and not, as appropriate. A block

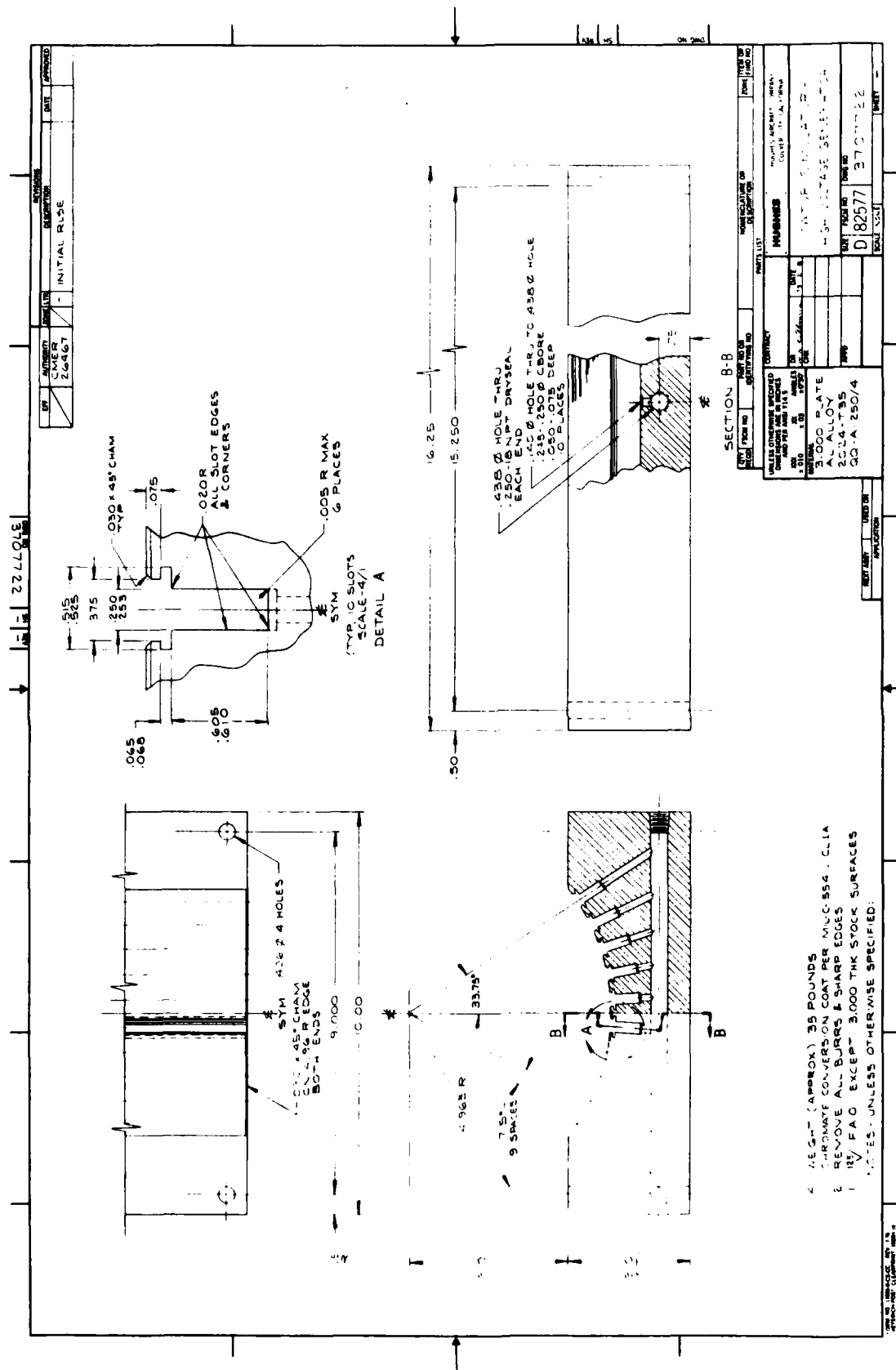


diagram of the test set-up is shown in Figure 2 for coil-to-ground tests, and in Figure 3 for turn-to-turn tests.

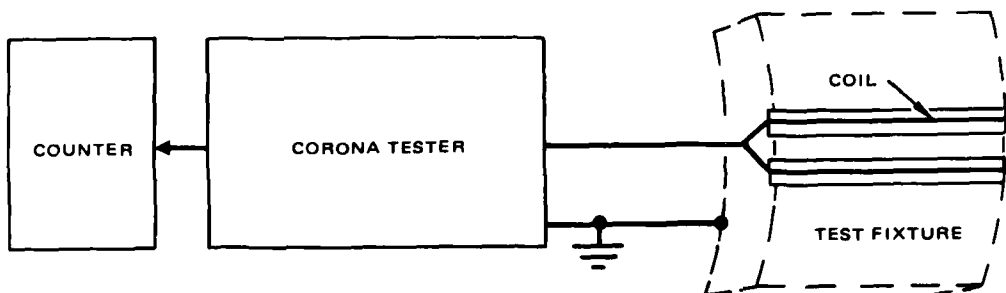


Figure 2. Set-up for corona test, coil to ground.

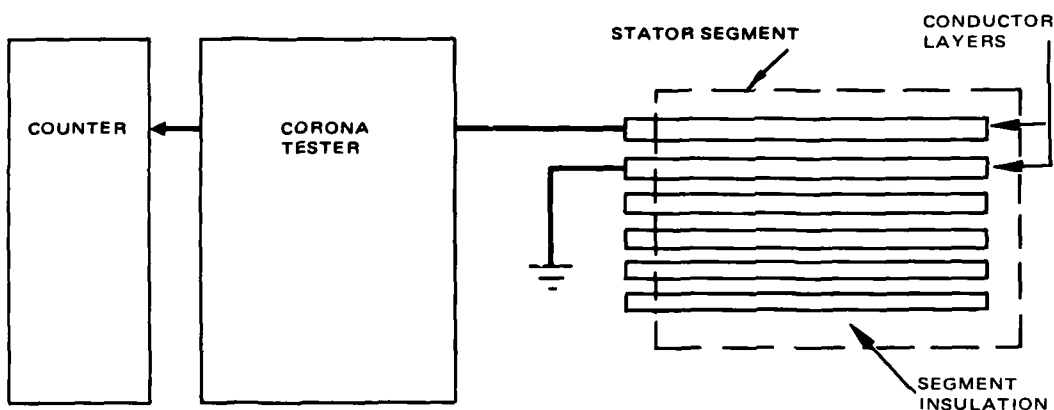


Figure 3. Set-up for corona test, turn-to-turn.

4.1.2 Corona Test Equipment

Electronic equipment to be used in these tests will be a heavily modified single ended corona detector originally manufactured by James G. Biddle Co., model 66-J-1964. This apparatus, shown in Figure 4, is equipped with an 8-channel bin counter and special power conditioning. It has an effective sensitivity of 20pC at 1 μ F, and a count rate in excess of 300 kHz.

The test fixture shown in Figure 1 will be equipped with heaters, sump, and gear-type pump to maintain the 100°C oil temperature and

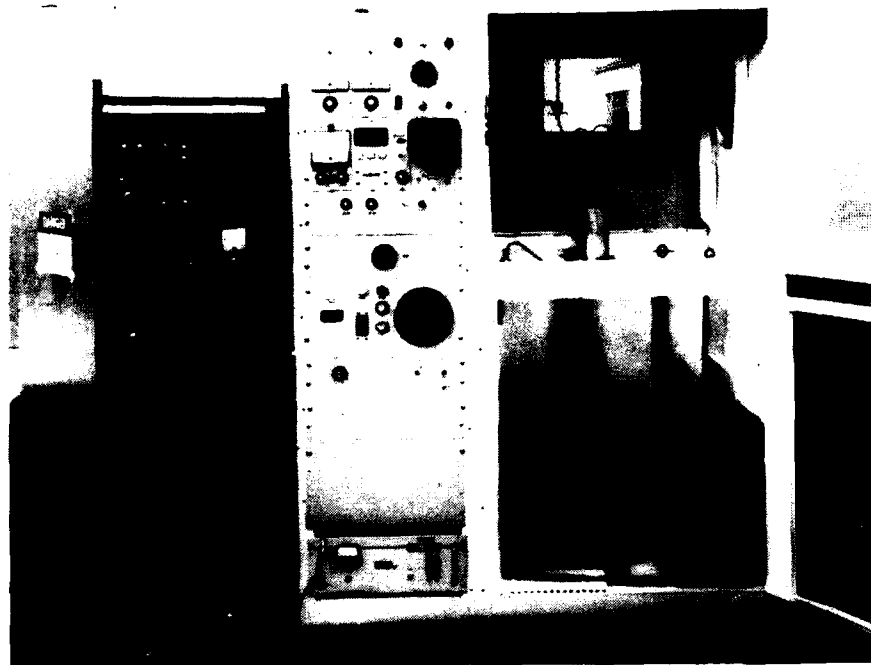


Figure 4. Corona test apparatus.

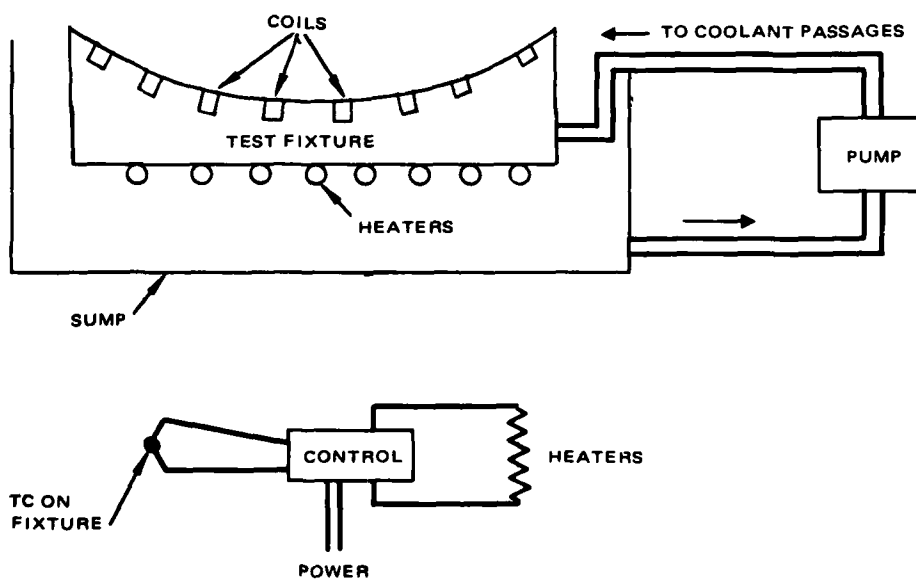


Figure 5. Schematic of complete test set-up.

required flow rate. A schematic of this set-up is shown in Figure 5. The test fixture will be mounted on a stand to the right of the corona test unit, and connections will be made through a field-controlled port.

For tests on segments, the same set-up will be used, except that room temperature tests may be run out side of the fixture in the normal way.

4.1.3 Corona Test Procedure

Corona tests will be run in conformance with ASTM standard D-1868, and IEEE Standard 454. Tests will be run both at room temperature and with the coolant at 100°C. The test sequence will be the same for both types of samples:

- 1) Measure corona inception voltage at 25°C
- 2) Measure corona extinction voltage at 25°C
- 3) Measure corona rate at operating stress (25°C)
- 4) Repeat (1-3) at 100°C.

4.1.4 Sample Corona Test Data Sheet

A sample corona test data sheet is shown:

s/n	Coil-to-Ground Tests						Remarks
	25°C			100°C			
	CIV	CEV	Q	CIV	CEV	Q	
1	3.2	3.1	0	2.9	2.8	23	
2	3.3	3.1	13	2.8	2.4	25	
3							
4							

CIV and CEV in kV, Q in pC/s.

4.1.5 Acceptance Criteria

Coils to be used in the life test will be expected to have CIV at 100°C greater than 3.5kV (RMS), but because of the short required duty coils with

lower CIV may also be tested. No turn-to-turn or phase-to-phase CIV testing is planned for full coils.

4.2 LIFE TEST

Life tests will be conducted to demonstrate the applicability of the developed insulation system to the particular engineering problem posed by service in Generator 28B371-1. The environment will duplicate the generator environment as closely as possible, per the requirements of paragraph 3.10 of the purchase description.

4.2.1 Life Test Set-Up

The fixture used to simulate the generator environment has been described in Section 4.1.1. Current and voltage will be supplied to the coils in the test fixture by an arrangement of power sources, as shown in Figure 6. Only complete coils will be tested.

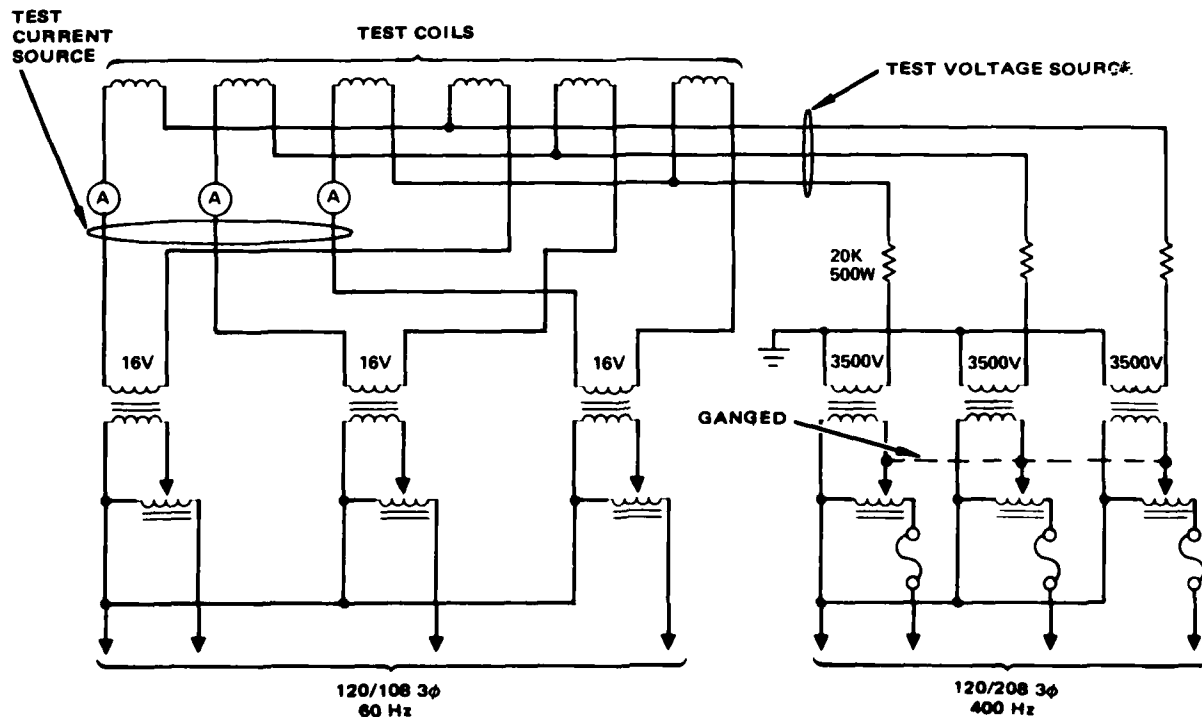


Figure 6. Life test schematic.

4.2.2 Life Test Equipment

In addition to the test fixture described in Sections 4.1.1 and 4.1.2, a 3 phase 400 Hz variac will be used to control the test voltage, and various other transformers will be used to supply the current (3 phase 60 Hz) and the test voltage (3 phase 400 Hz).

4.2.3 Life Test Procedure

The life test will be run at the conditions prescribed for 250 hours. If a coil failure occurs, the failed coil will be replaced, up to the limit of existing coils.

4.2.4 Sample Life Test Data Sheet

A sample life test data sheet is shown below:

<u>s/n</u>	<u>Hours</u>	<u>Failure</u>
1	250	None
2	250	None
3	135	to test fixture.

4.2.5 Acceptance Criteria

Coils which do not fail will be considered to have passed. A statistical analysis will define the significance of the test results.

4.3 BENDING TEST

The bending test is designed to exhibit the flexibility required of the insulation system used on the coils, particularly of the pitch coils.

4.3.1 Bending Test Set-Up

The required amount of bending was determined by watching assembly processes. The bending test will be performed using parts of the fixture described in 4.1.1.

4.3.2 Bending Test Equipment

No equipment is required except the fixture, noted above, and the corona test apparatus, described in paragraph 4.1.2.

4.3.3 Bending Test Procedure

It is required that, during assembly, the pitch coil be bent a small amount to allow another coil to slip underneath. The amount required is illustrated in Figure 7.

Coils will have coil to ground CIV measured before and after the test, to detect any damage. The procedure will be:

- 1) Measure CIV
- 2) Bend five (5) times
- 3) Visually inspect
- 4) Measure CIV.

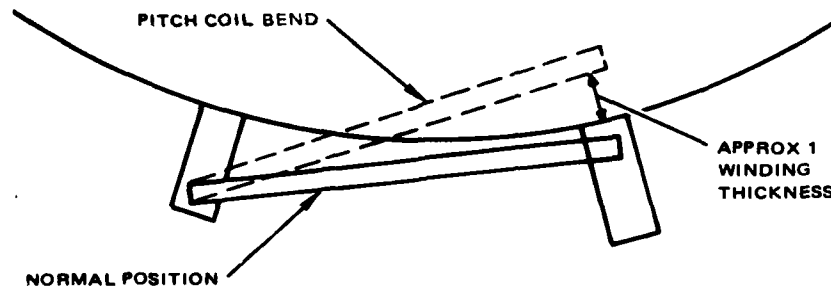


Figure 7. Amount of pitch coil bend.

4.3.4 Sample Bending Test Data Sheet

A sample bending test data sheet is shown below:

<u>s/n</u>	<u>CIV initial</u>	<u>CIV final</u>	<u>Visual</u>
1	3.45	3.25	Ok
2	3.51	3.62	Ok
3	3.46	1.75	crack

4.3.5 Acceptance Criteria

Acceptance will be based on freedom from mechanical damage (determined visually) and 10% or less decrease in CIV.

4.4 TEMPERATURE CYCLING

The generator stator insulation is expected to withstand repeated abrupt temperature cycles in operation. This test assures that thermal stresses do not compromise the integrity of the insulation.

4.4.1 Temperature Cycling Test Set-Up

Samples will be testing in an automatic thermal shock machine, which consists of 2 chambers and a transfer mechanism. Stator segments will be used, and they will be unpowered during the test.

4.4.2 Temperature Cycling Test Equipment

These tests involve an automatic thermal shock machine, such as the Dyna 8000, and the corona detection machinery described in paragraph 4.1.2.

4.4.3 Temperature Cycling Test Procedure

Tests will be conducted per MIL-STD-810C, method 503.1, or equivalent, except that the maximum temperature will be +200°C and the lowest temperature 0°C. The test sequence is:

- 1) Measure CIV between turns
- 2) Cycle 30 times

3) Measure CIV and inspect

4.4.4 Sample Thermal Cycle Test Data Sheet

A sample data sheet is shown below:

<u>s/n</u>	<u>Initial CIV</u>	<u># cycles</u>	<u>Final CIV</u>	<u>Visual</u>
1	3.45	30	3.51	Ok
2	3.56	29	3.42	Ok
3	3.30	31	2.41	Cracked.

4.4.5 Acceptance Criteria

Acceptance will be based on freedom from mechanical damage (visual) and 10% or less decrease in CIV.

4.5 DIELECTRIC BREAKDOWN

This test is a generally-used insulation test required by paragraph 3.10 of the purchase description. It is a destructive test.

4.5.1 Breakdown Test Set-Up

The set-up and samples are identical to those described in paragraph 4.1.1. The corona test apparatus is also used as a dielectric breakdown tester.

4.5.2 Breakdown Test Equipment

The equipment is identical to that described in 4.1.2. The corona test apparatus has a motor-driven breakdown tester built in.

4.5.3 Breakdown Test Procedure

Tests will be run both at room temperature and at 100°C per ASTM D-149.

4.5.4 Sample Breakdown Test Data Sheet

Turn-to-turn test

<u>s/n</u>	<u>Temperature</u>	<u>Voltage</u>	<u>Visual</u>
1	25°C	5.45 kV	
2	100°C	3.21 kV	
3	100°C	4.35 kV	

4.5.5 Acceptance Criteria

All values must be above the operating point.

5.0 OVERALL TEST PLAN

It is anticipated that some tests will be run in sequence, some in series. This section gives the general plan.

5.1 ARRANGEMENT OF TESTS

The tests will be conducted in the following time phase:

- | | | | |
|-----|---------------------|---|----------------|
| I: | Corona | } | Simultaneously |
| | Bending | | |
| | Breakdown | | |
| II: | Temperature Cycling | } | Simultaneously |
| | Life Test | | |

5.2 NUMBER OF SPECIMENS

The number of specimens to be used in each test is shown in the following table

<u>Test</u>	<u>Full Coils</u>	<u>Segments</u>	<u>Destructive?</u>
Corona	10	4	No
Bending	4	0	No
Breakdown	3	3	Yes
Temperature	0	6	No
Life	10	0	No
Total	27	13	

The number of samples to be made is probably less than the totals, since, for example, coils which test acceptably on corona may then be used for the life test.

6.0 UNUSUAL TESTS

None of these tests is particularly unusual. All tests do not have equal weight, the life test being more significant than breakdown, for example.

7.0 SCHEDULE

The test schedule is given in Figure 8.

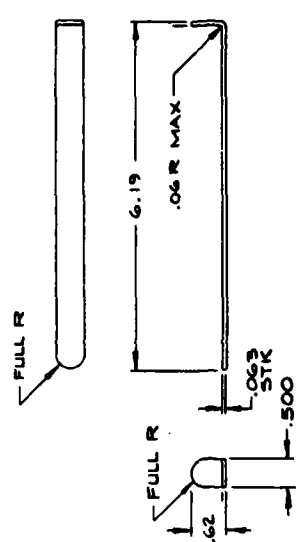
TEST	SCHEDULE, 1980			
	15 JUNE 30	1 JULY 31	1 AUGUST 31	
CORONA MEASUREMENT		←→		
BENDING	←→			
BREAKDOWN	←→			
TEMPERATURE CYCLING		←→		
LIFE			←→	

Figure 8. Planned proof-of-design test schedule.

APPENDIX D
SLOT SIMULATOR
TEST FIXTURE

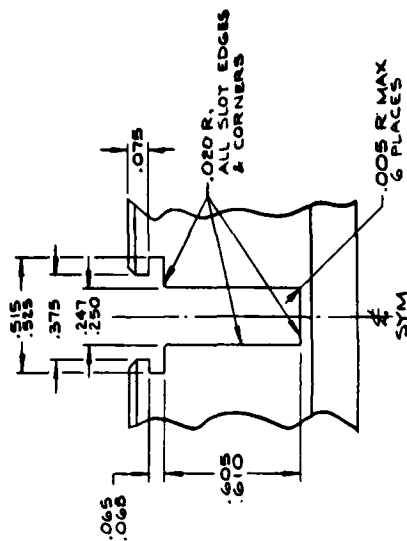
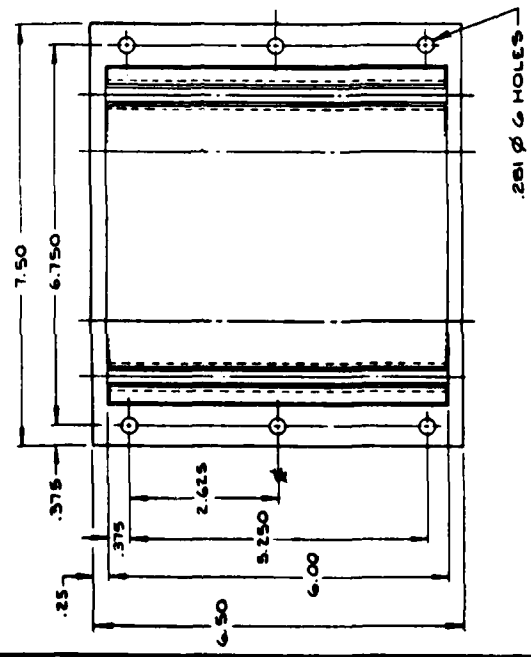
	DATE	SIN	REV	A
1000	10/10/80	1	1	1

ATTENSIÓN					
EFE	AUTHORITY	ZONE/LTR	DESCRIPTION	DATE	APPROVED
	CMER 26467	-	INITIAL RLSE	7-11-68	FOR

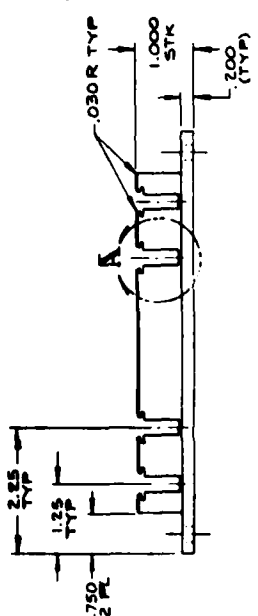


4. PASSIVATE PER QQ-P-35, TYPES I, II, III OR VI
3. 4 EACH REQD PER UNIT (REF)
2. .015 R, ALL EDGES
1. MATL: .063 SHEET CRES. COMP 301,
QQ-S-766, HALF HARD
NOTES:
TOP STICK -

TOP STICK - 98



(TYP. 4 SLOTS)
SCALE - 4/1
DETAIL A



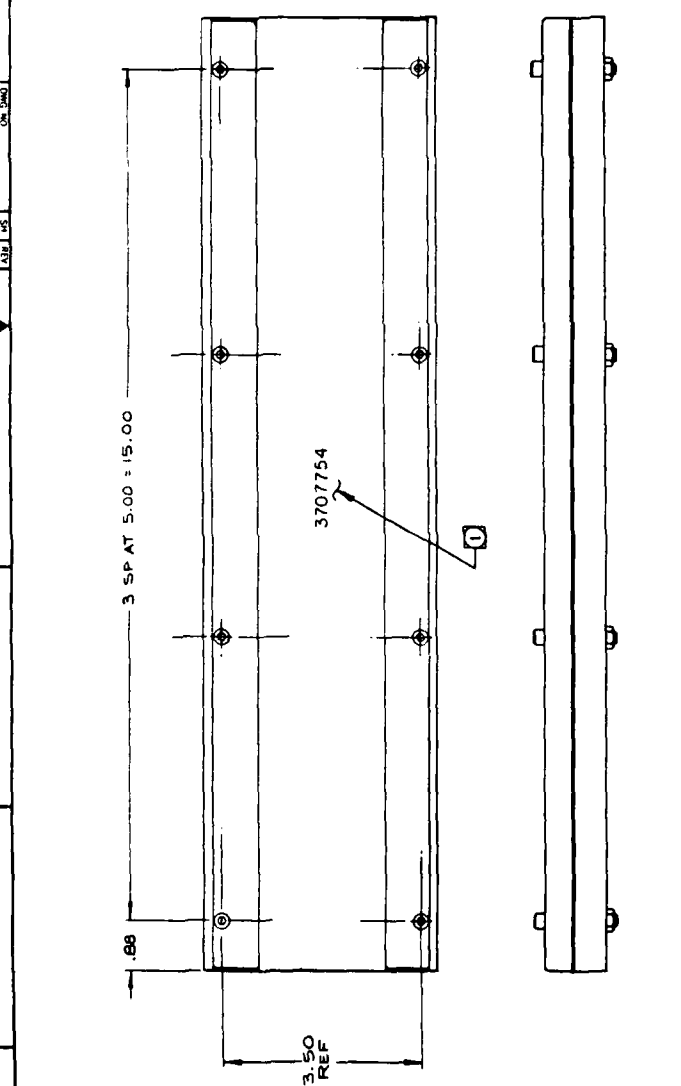
3. REMOVE ALL BURRS & SHARP EDGES
2 $\frac{13}{16}$ F.A.O.
1 MATL: 1.000 PLATE BRASS. NAVAL HOT ROLL. ALLOY 464,
CO. B-639. HALF HARD (OR EQUIV)
NOTES:

BASE - 99

[illegible]

APPENDIX E
COIL MOLD

REV. SHEET	DATE	APPROVED
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24		
25		
26		
27		
28		
29		
30		
31		
32		
33		
34		
35		
36		
37		
38		
39		
40		
41		
42		
43		
44		
45		
46		
47		
48		
49		
50		
51		
52		
53		
54		
55		
56		
57		
58		
59		
60		
61		
62		
63		
64		
65		
66		
67		
68		
69		
70		
71		
72		
73		
74		
75		
76		
77		
78		
79		
80		
81		
82		
83		
84		
85		
86		
87		
88		
89		
90		
91		
92		
93		
94		
95		
96		
97		
98		
99		
100		



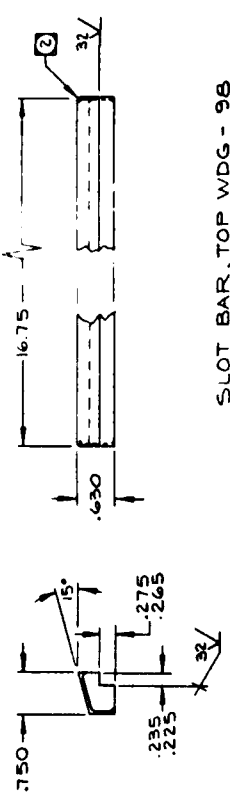
REV	STATUS	SH	1	2	3
1	SH	1	2	3	
2	LTR	-	-	-	

REV	STATUS	SH	1	2	3
1	SH	1	2	3	
2	LTR	-	-	-	

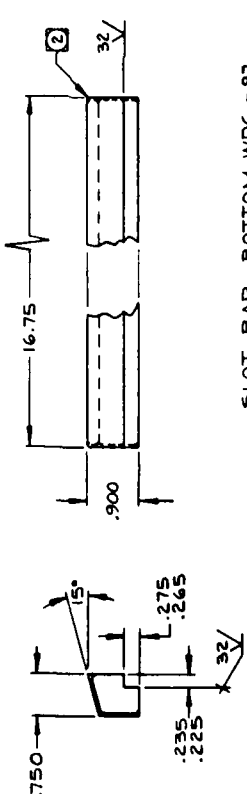
HUGHES		HUGHES AIRCRAFT COMPANY CULVER CITY, CALIFORNIA	
POTTING FIXTURE - STATOR COIL			
DATE	10/25/77	REV NO	3707754
SCALE	1/1	SHEET 1 OF 3	

2 MATCH DRILL BOTH SLOT BARS (-97 & -98) FLUSH WITH
BASE PLATE (-99) USING .173/.178 DIA HOLES
MARK PER HPB-S, TYPE 1, CLASS 1, .19 INCH
HIGH CHARACTERS; LOCATE APPROX AS SHOWN
NOTES - UNLESS OTHERWISE SPECIFIED:

REV	DESCRIPTION	DATE	APPROVED
1	INITIAL RISE		
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			
26			
27			
28			
29			
30			
31			
32			
33			
34			
35			
36			
37			
38			
39			
40			
41			
42			
43			
44			
45			
46			
47			
48			
49			
50			
51			
52			
53			
54			
55			
56			
57			
58			
59			
60			
61			
62			
63			
64			
65			
66			
67			
68			
69			
70			
71			
72			
73			
74			
75			
76			
77			
78			
79			
80			
81			
82			
83			
84			
85			
86			
87			
88			
89			
90			
91			
92			
93			
94			
95			
96			
97			
98			
99			
100			



SLOT BAR, TOP WDG - 98



SLOT BAR, BOTTOM WDG - 97

- 5 NICKEL PLATE PER QQ-N-290, CL. 1, GR. D, E OR F
 - 4 INSIDE CORNER RADIUS = .015 MAX TYP
 - 3 REMOVE ALL BURRS & SHARP EDGES
 - 2 .06 R (APPROX) 3 CORNERS & 2 EDGES INDICATED, EACH END
 - 1 .125 F.A.O.
- GENL NOTES - UNLESS OTHERWISE SPECIFIED:

QTY	FRM NO	PART NO OR IDENTIFYING NO	MANUFACTURE OR IDENTIFYING NO	DATE	APPROVED
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES AND PER ANSI Y14.5					
MATERIAL STEEL					
BAR OR PLATE					
7.50 THK					
C1018 CD					
ASTM-A-108					
(OR EQUIV)					
NEXT ASST USED ON APPLICATION					
HUGHES					
HUGHES AIRCRAFT COMPANY					
OAKLAND, CALIFORNIA					
POTTING FIXTURE -					
STATOR COIL					
SIZE FRM NO					
D 82577 3707754					
SCALE 1/1					
SHEET 2					

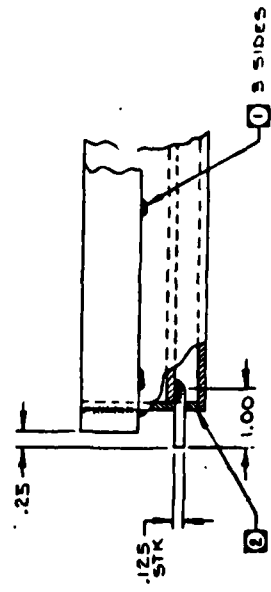
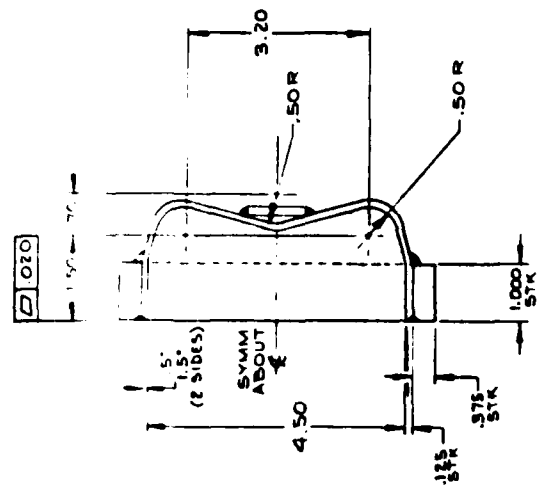
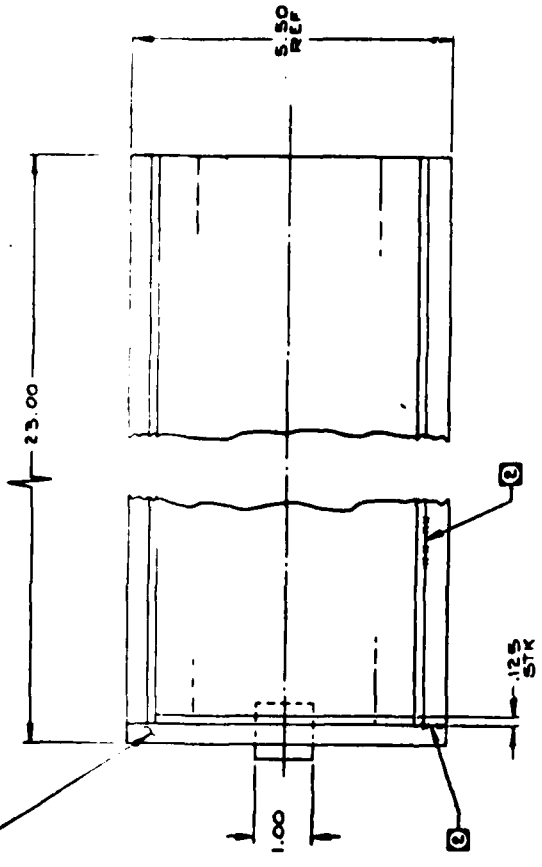
APPENDIX F
BOX MOLD

APPENDIX G
REDESIGNED COIL MOLD

APPENDIX H
REDESIGNED BOX MOLD

127771 127771

CORNER JOINT CONFIGURATION &
END PLATE CONFIGURATION OPTIONAL



CAVITY - 9B

- 3 REMOVE ALL BURRS & SHARP EDGES
 - 2 SOLID FUSION WELD ALL EXTERNAL JOINTS AND SEAMS FOR VACUUM TIGHT SEAL PER MIL-W-8604
 - 1 SKIP OR SPOT WELD IN POSITION AS NECESSARY
- NOTES - UNLESS OTHERWISE SPECIFIED:

LOW PRESS NO	DATE REC'D	DATE PLACED IN	DATE PLACED IN
PARTS LIST			
HUGHES			
POTTING MOLD -			
STATOR COIL			
D 82577 3707771			
D 82577 3707771			
D 82577 3707771			

APPENDIX I
DESIGN CALCULATIONS FOR
TURN TO TURN TEST APPARATUS

APPENDIX I DESIGN CALCULATIONS FOR TURN TO TURN TEST APPARATUS

The magnetic flux density, B_{\max} , of the core was calculated from

$$B_{\max} = \frac{3.49 E 10^6}{f A_c N (SF)} \quad (I-1)$$

where:

$E = 100$ volts

$f = 1600$ Hz

$A_c =$ core cross section

$N =$ number of turns = 1

$SF =$ space factor of core = 0.9

and

$$B_{\max} = \frac{3.49 \times 100 \times 10^6}{1600 \times 17 \times 1 \times 0.9} = 14.3 \text{ k Gauss}$$

Equation (I-1) can be used to ascertain the step-up ratio of the test apparatus. The circuit diagram is shown in Figure I-1, where E_1 is the input voltage and E_2 the voltage in the stator coil. The step-up ratio is E_2/E_1 .

From Equation I-1,

$$E_1 = B_{\max} A_c f N (SF) \times 3.49 \times 10^{-6}$$

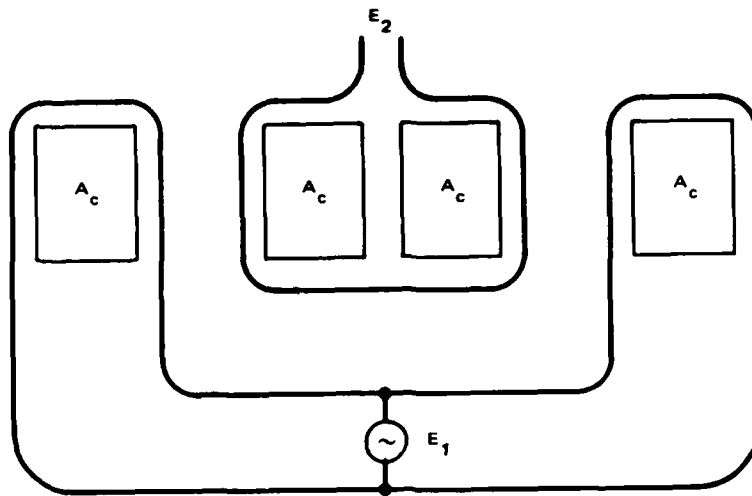


Figure I-1. Schematic circuit of turn-to-turn test fixture.

and

$$E_2 = B_{\max}(2A_c) fN(\text{SF}) \times 3.49 \times 10^{-6}$$

For E_1 , $N = 1$ and for E_2 , $N = 6$

Taking the ratio of E_2/E_1 the step-up ratio is

$$\frac{E_2}{E_1} = 12$$

The primary inductance was calculated from

$$L = \frac{3.2 N^2 A 10^{-8}}{\frac{\ell}{\mu} + \alpha} = 544 \times 10^{-6} \text{ H} \quad (\text{I-2})$$

where:

ℓ = core length = 6 in.

μ = permeability of core = 40,000

α = length of air gap = 0.002 in.

For pure inductance, the current is

$$I = \frac{V}{\omega L} = 18.3 \text{ A}$$

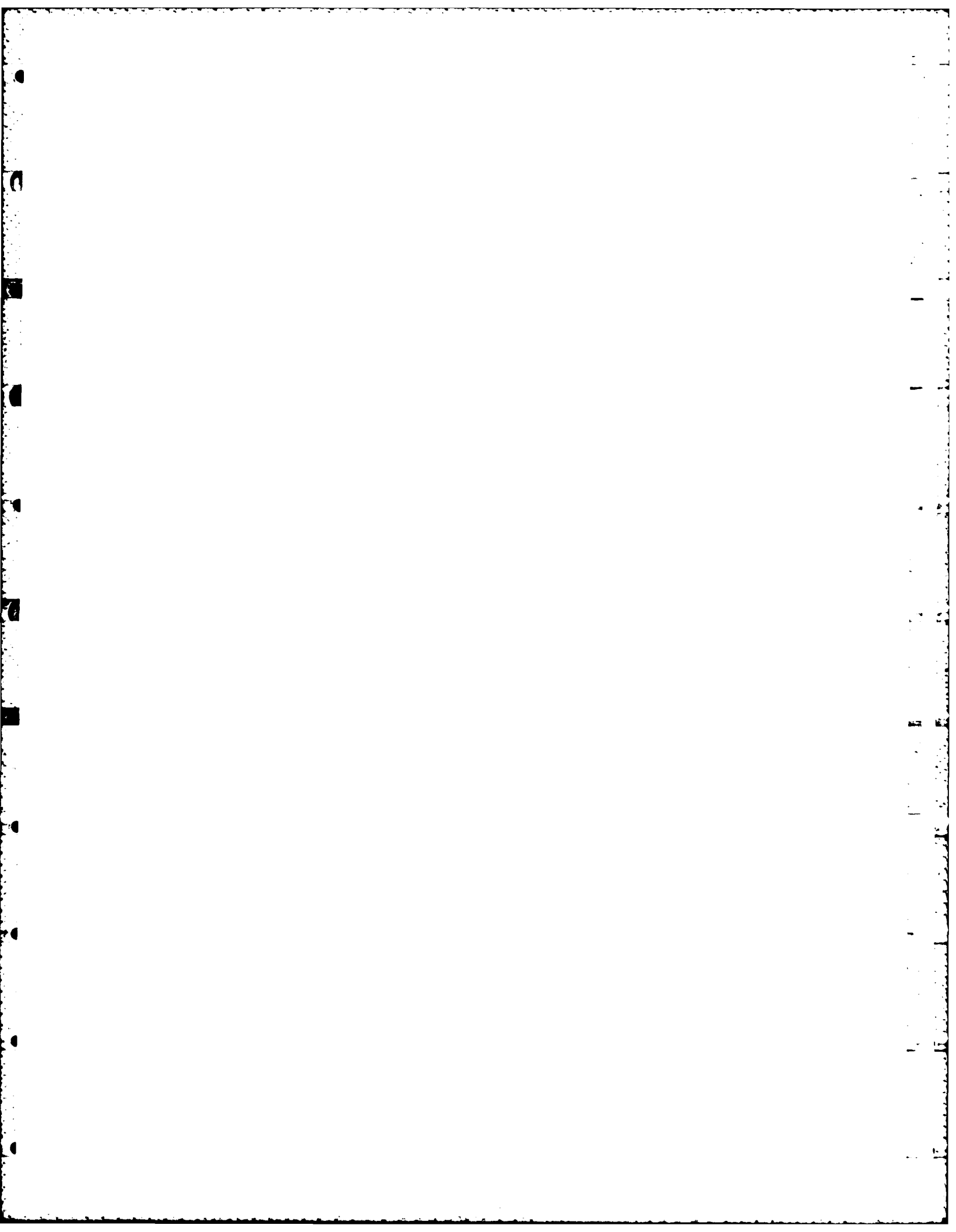
The current was reduced by adding capacitance in parallel with the primary to form a resonant circuit. For $C = 20 \times 10^{-6} \text{ F}$ which is near resonance the parallel impedance is

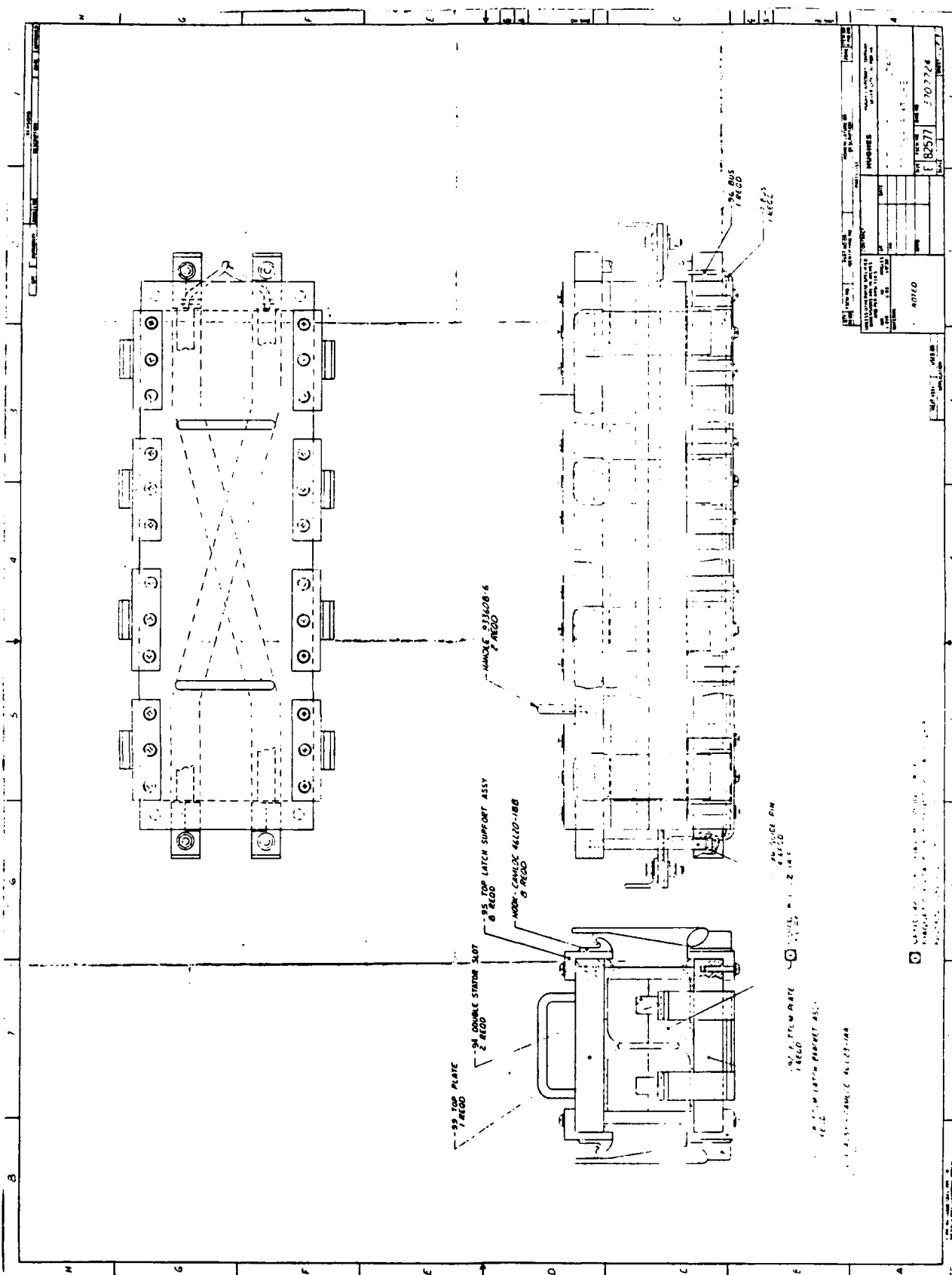
$$Z = \frac{\omega L}{1 - \omega^2 LC} = 54.9 \text{ } \Omega$$

and

$$I = \frac{V}{Z} = 1.82 \text{ A}$$

APPENDIX J
TURN TO TURN TEST FIXTURE





NOTED		82577		370724	
REVISION		DATE		BY	
1		10/1/54		J. L. H.	
2		10/1/54		J. L. H.	
3		10/1/54		J. L. H.	
4		10/1/54		J. L. H.	
5		10/1/54		J. L. H.	
6		10/1/54		J. L. H.	
7		10/1/54		J. L. H.	
8		10/1/54		J. L. H.	
9		10/1/54		J. L. H.	
10		10/1/54		J. L. H.	
11		10/1/54		J. L. H.	
12		10/1/54		J. L. H.	
13		10/1/54		J. L. H.	
14		10/1/54		J. L. H.	
15		10/1/54		J. L. H.	
16		10/1/54		J. L. H.	
17		10/1/54		J. L. H.	
18		10/1/54		J. L. H.	
19		10/1/54		J. L. H.	
20		10/1/54		J. L. H.	
21		10/1/54		J. L. H.	
22		10/1/54		J. L. H.	
23		10/1/54		J. L. H.	
24		10/1/54		J. L. H.	
25		10/1/54		J. L. H.	
26		10/1/54		J. L. H.	
27		10/1/54		J. L. H.	
28		10/1/54		J. L. H.	
29		10/1/54		J. L. H.	
30		10/1/54		J. L. H.	
31		10/1/54		J. L. H.	
32		10/1/54		J. L. H.	
33		10/1/54		J. L. H.	
34		10/1/54		J. L. H.	
35		10/1/54		J. L. H.	
36		10/1/54		J. L. H.	
37		10/1/54		J. L. H.	
38		10/1/54		J. L. H.	
39		10/1/54		J. L. H.	
40		10/1/54		J. L. H.	
41		10/1/54		J. L. H.	
42		10/1/54		J. L. H.	
43		10/1/54		J. L. H.	
44		10/1/54		J. L. H.	
45		10/1/54		J. L. H.	
46		10/1/54		J. L. H.	
47		10/1/54		J. L. H.	
48		10/1/54		J. L. H.	
49		10/1/54		J. L. H.	
50		10/1/54		J. L. H.	
51		10/1/54		J. L. H.	
52		10/1/54		J. L. H.	
53		10/1/54		J. L. H.	
54		10/1/54		J. L. H.	
55		10/1/54		J. L. H.	
56		10/1/54		J. L. H.	
57		10/1/54		J. L. H.	
58		10/1/54		J. L. H.	
59		10/1/54		J. L. H.	
60		10/1/54		J. L. H.	
61		10/1/54		J. L. H.	
62		10/1/54		J. L. H.	
63		10/1/54		J. L. H.	
64		10/1/54		J. L. H.	
65		10/1/54		J. L. H.	
66		10/1/54		J. L. H.	
67		10/1/54		J. L. H.	
68		10/1/54		J. L. H.	
69		10/1/54		J. L. H.	
70		10/1/54		J. L. H.	
71		10/1/54		J. L. H.	
72		10/1/54		J. L. H.	
73		10/1/54		J. L. H.	
74		10/1/54		J. L. H.	
75		10/1/54		J. L. H.	
76		10/1/54		J. L. H.	
77		10/1/54		J. L. H.	
78		10/1/54		J. L. H.	
79		10/1/54		J. L. H.	
80		10/1/54		J. L. H.	
81		10/1/54		J. L. H.	
82		10/1/54		J. L. H.	
83		10/1/54		J. L. H.	
84		10/1/54		J. L. H.	
85		10/1/54		J. L. H.	
86		10/1/54		J. L. H.	
87		10/1/54		J. L. H.	
88		10/1/54		J. L. H.	
89		10/1/54		J. L. H.	
90		10/1/54		J. L. H.	
91		10/1/54		J. L. H.	
92		10/1/54		J. L. H.	
93		10/1/54		J. L. H.	
94		10/1/54		J. L. H.	
95		10/1/54		J. L. H.	

APPENDIX K
CONDUCTIVE SOLUTION

APPENDIX K
CONDUCTIVE SOLUTION

The conductive solution contains the following chemicals:

5 gm potassium sulphate, K_2SO_4

500 cc distilled water

1cc phenolphthalien

The phenolphthalien can be made up from:

0.05 gm phenolphthalien (powder)

50 ml ethanol

50 ml distilled water

END

FILMED

8-83

DTIC